Barriers to Expertise in Citizen Science Games

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ABSTRACT

Expertise-centric citizen science games (ECCSGs) can be powerful tools for crowdsourcing scientific knowledge production. However, to be effective these games must train their players on how to become experts, which is difficult in practice. In this study, we investigated the path to expertise and the barriers involved by interviewing players of three ECCSGs: Foldit, Eterna, and Eyewire. We then applied reflexive thematic analysis to generate themes of their experiences and produce a model of expertise and its barriers. We found expertise is constructed through a cycle of exploratory and social learning but prevented by instructional design issues. Moreover, exploration is slowed by a lack of polish to the game artifact, and social learning is disrupted by a lack of clear communication. Based on our analysis we make several recommendations for CSG developers, including: collaborating with professionals of required skill sets; providing social features and feedback systems; and improving scientific communication.

CCS CONCEPTS

• **Human-centered computing** → *Empirical studies in interaction design*; *Interaction design theory, concepts and paradigms*; User centered design; • **Applied computing** → *Collaborative learning*.

KEYWORDS

citizen science games, expertise, game design, thematic analysis

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1 INTRODUCTION

Citizen science games (CSGs) can be a powerful tool for crowdsourcing scientific advancements [38]. Yet, for them to succeed, they must effectively train their players in how to play. This is especially true for *expertise-centric* CSGs (ECCSGs) — a recent term coined by Keep [97] — such as Foldit [40] and Eterna [156]. In these games, citizen scientists achieve a complementary domain expertise which provides novel expertise to the scientific domain experts [97]. Contrast this with *data-centric* [97] projects such as iNaturalist [133], a platform where citizen scientists contribute images and image labels rather than human computation and creativity. Data-centric CSGs include Phylo and Borderlands Science [192], games which require little training or expertise before players can make meaningful contributions. In these games, the scientific problem being worked on is not a challenging task, but challenging in the sheer amount of data that needs human processing. Expertise-centric games, on the other hand, take months to years of play to fully understand the domain enough to make meaningful contributions, such as protein and RNA design and virtual neuron reconstruction — the tasks of Foldit, Eterna, and Eyewire respectively [40, 156, 178].

The value of CSGs is therefore twofold. The first value regards socially accessible science, "providing the public with access to important and challenging problems facing science and society" [180]. This includes not only being able to physically access opportunities to contribute to science, but cognitive access (understanding why they are able to contribute and how their contribution is important) and social access (making contributions a socially acceptable, and even encouraged, activity to engage in). The second value is practicality for scientific advancement: empowering citizens to solve these challenging problems which could otherwise take decades of scientific effort. Depending on how one classifies contributions, this can take several forms, as discussed below in subsection 2.1 and Table 1. Of note, the unique contribution of ECCSGs is in solving complex problems and providing explanations for how they are solved.

Toward this goal, ECCSGs attempt to capture the motivational powers of collaboration, competition, and gamification [16, 43, 88, 91, 153, 177, 194]. Although this model is theoretically sound, effective development of an ECCSG requires enabling the players to gain this complementary domain expertise. In practice, this is very, very difficult.

Why? What are the barriers to expertise, what are the challenges that players face when they are onboarded into one of these CSGs? This is the research question of the current study, which tries to identify "breakdowns" [86, 87] in CSG onboarding, defined by Sharples as "observable critical incidents where a learner is struggling with the technology, asking for help, or appears to be labouring under a clear misunderstanding" [166, p. 10]. While some breakdowns can lead to learning, others can lead to catastrophic disengagement [87]. Therefore, a better understanding of which kinds of breakdowns are occurring in ECCSG onboarding — and how — is important to supporting players' expertise development for solving scientific challenges.

To speak plainly about why this work is important, supporting expertise in ECCSGs can lead to greater quantity and quality of scientific data for research in fields like protein and RNA design. More broadly, by understanding expertise development we may be able to gain new insights into how to train learners in new

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domains for which little to no training materials have yet been developed. And on the other hand, a failure to deliver effective training to ECCSG participants would risk these games failing to draw in an audience, potentially leading to widespread distrust and abandonment of the citizen science gaming model entirely.

Therefore, we examine the research question "What is the path to expertise in ECCSGs and what are the major barriers along that path?" This is achieved through interviews with ECCSG players of Foldit, Eterna, and Eyewire about their skills and experiences, and we explore the data using a deductive and constructionist application of reflexive thematic analysis [20, 21]. In doing so, we attempt to identify the golden path[1] to expertise in ECCSGs and any barriers along that path. More generally, the study of ECCSGs provides key insights into the design of game-based learning, crowdsourcing, and community knowledge construction. Although we list most recommendations in Table 3 as specific to ECCSGs, many of the principles can serve as inspiration for educational games, serious games, and other citizen science projects.

The primary contribution of this paper is a model of the path to expertise in ECCSGs and barriers along that path. We find that the path to expertise is a cycle of exploratory learning and social learning. The three dominant barriers to this cycle are missing instruction, missing polish, and missing communication. Specifically, new players struggle to understand how to interact with the game and the broader, holistic research loop of how gameplay and science connect. Then, frictions with the user interface, technology, and gameplay slow or hinder exploratory learning. And finally, several communication barriers prevent the social learning that would otherwise ameliorate these other failings, including inaccessible and infrequent scientific communication, and the gatekeeping of community content creation.

Based on these findings, we provide recommendations for CSG developers, for example collaborating with professionals of complementary skill sets in community management, UI/UX, software development, game design, instructional design, and science journalism. We further recommend providing social features in and outside of the game, teaching the big picture first, and improving scientific communication with the players, among other recommendations listed in Table 3. However, in discussing these potential or partial solutions, we also note broader complications with the ECCSG model, such as their lack of financial sustainability and the accessibility issues to participation brought on by requiring expertise.

2 BACKGROUND

2.1 Citizen Science and Related Terms

Let us briefly define and contextualize citizen science.[2] Citizen science is a subset of public participation in scientific research. This superset also contains crowdsourcing and community-based natural resource management, among others [54, 80, 167]. There are many working definitions of citizen science, which largely describe public volunteer efforts toward scientific work [54]. For the purpose of this article, we focus on "science-oriented virtual projects" [28, 196], wherein volunteers participate in goal-oriented scientific activities mediated by information and communications technology.

With respect to the contributions provided by a given citizen science project, there are many typologies which categorize contribution models. These include, among others: Brabham's crowdsourcing typology [19], Schrier's knowledge games typology [162], Rafner et al.'s framework of citizen science tasks [151], and Wiggins & Crowston's citizen science typology [196]. For the purpose of this article, we define contributions by four components: volunteer action, data origin, project output, and research goal. For example, in Galaxy Zoo [61] volunteers classify images of galaxies (action) from telescope imagery (data origin) which creates a database of classified galaxies (project output) for further scientific research on galaxies (research goal). Citizen science projects can have a variety of non-exclusive research goals, ranging from education, to environmental science, to community impact, and more [196]. However, to define the scope of ECCSGs, we exclude goals and focus only on volunteer action, data origin, and project output. See Table 1 for our classification of CSG contribution models.

In this table, data collection from the "environment" includes everything external to the volunteer. Data from the volunteer refers to citizen psych-science [90], described in subsection 2.4. For the data origins of expertise-centric projects, "provided" means provided by the researchers (e.g., in Quantum Moves, there are specific problems to solve), "selected" means that the volunteers have flexibility in how they choose or solve the provided problems (e.g., in Foldit and Eterna, players design structures to solve a problem), and "made" means that volunteers create their own problems within the project's domain. Although no projects to our knowledge focus on this type of data origin, one example comes from Eterna in which a player used the game to produce their own scientific research [142]. Also note that this typology is not comprehensive and excludes less relevant (to ECCSGs) contribution models such as volunteer computing.

For more details on the typologies and classifications of citizen science, crowdsourcing, and public participation in research, we refer to previous literature that has already thoroughly explored this topic [28, 54, 75, 196]. Meanwhile, let us assume that — for this article — citizen science is the process of volunteers engaging virtually in scientific research, and that ECCSGs have the unique affordance of engaging volunteers in scientific problem solving. In our case, this happens by means of playing citizen science games (CSGs). However, we first explore why the "game" aspect is critical, and specifically how players experience games.

2.2 Player Experience in Games

Before there were CSGs there were games, and scholars needed to understand how players experience them. To this, much work has examined how players engage with games [30, 52, 82, 160, 173, 195] and what makes games playable [46, 105, 134, 138]. Within the realm of player experiences, the field of game-based learning focuses specifically on how players learn from games — often regarding games as constructionist learning environments [48, 68]. As instructional tools, games offer experiential learning via a range of mechanisms including active and discovery learning, forming

[1] In the games industry (and other user-centric industries), a *golden path* is the sequencing of activities leading to the perceived ideal experience or optimal outcome [181].
[2] Also called community science in response to concerns about the exclusionary criterion of "citizen" [123].

Classification	**Expertise-centric cit. sci.**			**Data-centric cit. sci.**		
Volunteer action	Problem solving			Data analysis	Data collection	
Data origin	Provided	Selected	Made	Provided	Environment	Volunteer
Project output	Dataset or trained algorithm or strategy learning (generally or about this problem)			Dataset or trained algorithm		
Example	Quantum Moves	Foldit	Eterna	Galaxy Zoo	iNaturalist	Sea Hero Quest

Table 1: A typology of citizen science input/output structures for situating CSG and ECCSG contributions. ECCSGs can uniquely contribute information about how humans solve problems, either generally or specific to the domain of study. See the above text in Section 2.1 for definitions of data origin.

affinity groups, cycles of expertise, well-ordered problems, and simplifying conditions [64, 66, 68, 154].

Yet, there are still times when players don't connect with a game, when the game-user interaction breaks down. Iacovides et al. [86, 87] explored this phenomenon and identified three types of breakdowns: Action (failure to execute an in-game action), Understanding (failure to figure out what to do), and Involvement (failure to engage, such as from boredom or frustration). They further found that macro-level expectations of the game were informed by prior experience, other players, and the wider community. Moreover, continued involvement (at the micro-level) depends on meeting expectations, both internal to the game (such as in-game rewards) and externally (such as the price to purchase the game). Lastly, a key factor for involvement is the experience of agency, which is reduced if players do not believe that they have a meaningful impact within the game world. So players can experience breakdowns when their expectations are not met or they don't perceive their agentic influence on the game.

Zooming back out, breakdowns are one type of friction along a player's path to expertise in a game. Expertise, in short, occurs when an individual "chunks" their knowledge into cognitive schemata in order to process information quicker and easier [113, 148, 163]. This has the added effect of experts seeing and representing problems differently from novices, because experts rely on structural rather than surface features for problem-solving [29, 31]. Within games, researchers have studied expertise in depth, from what players learn [51, 59] to how they learn [81, 83, 158] to how to figure out what they learn [176]. Yet, ECCSGs are a separate domain entirely and an interesting but unexplored niche for understanding expertise in games. But first, what are CSGs, and why do we care?

2.3 Player Experience in Citizen Science Games

As alluded to in the Introduction, CSGs are games wherein players contribute to scientific progress, such as via collecting, providing, labeling, sorting, or analyzing data [130, 197]. CSGs can be either games or gamified projects, and it's worth disambiguating those terms. Although usage varies widely, the most popular definition for gamification in the 2010s comes from Deterding et al. [49] who define it as "the use of game design elements in non-game contexts." What distinguishes a game from a gamified activity includes, among other factors based on one's choice of definition, the psychosocial contexts in which the activity is understood [47], the consequentiality of game actions [94], and the design intent (whether the activity's purpose is gamefulness or whether gameful elements are employed as a strategy toward another goal) [49]. The gamification of citizen science has arisen from a need to motivate a wider audience to engage [144]. To this end, much of citizen science and crowdsourcing has been gamified, and previous literature has reviewed its usage and effectiveness across the field [127, 128].

Similarly, much research has been done to examine what motivates citizen science players engaging with full-fledged games. To summarize that body of work succinctly: players are drawn to CSGs by their previous interests in science, the specific research topic, curiosity, and a desire to contribute to research [43, 50, 88, 91]. Their continued engagement requires recognition for their contributions, feedback, enjoying the task, proper pacing, and teamwork [88, 91, 153]. Players are motivated by interactions with others, community building, intellectual challenge, sharing the same goals and values with the project, helping others, learning new information, and feeling a sense of belonging with their team [43, 50, 91]. Furthermore, intrinsic motives (e.g., interest in the topic) are critical for long-term participation, while extrinsic factors (e.g., appealing software) are better suited for recruitment [9, 56, 79]. Other motivational factors that have been researched, with mixed results, include narrative [147] and gamification [17, 57, 140]. Studies have also been done to understand the ways in which participants engage with citizen science. Scholars identified five profiles of engagement: loyal, hardworking, persistent, lurking, and visitors [9, 139]. We expect that only the first three forms of participation gain expertise; however, lowering the barriers described in this work may also serve to admit lurkers and visitors into further engagement.

Synthesizing these factors, Jennett et al. developed the Motivation-Learning-Creativity (MLC) model [91]. Their model describes citizen science participation as initiated by a motivating interest in science. Then participants learn via participating at the micro- and macro-levels. Next, participants identify as a member of the community, which finally leads to creative contributions. Both identity and creativity then reinforce the motivation to participate. As shown in this study as well, Jennett and her colleagues highlight the importance of social learning, community building, and sharing. Participant learning is notably achieved through contributing, social interaction, using external resources and project documentation, and sharing personal creations, and as a result participants gain several learning outcomes including more knowledge on the scientific topic as well as scientific literacy. The MLC model is echoed in our findings as we identify expertise as a function of participation and social learning. Notably, the creativity component of MLC includes personal creations such as developing helper tools and resources and discussing ideas. However, we describe in Section 4.4 how there are barriers specific to ECCSGs which prevent this creativity from flourishing.

Despite the great amount of research on motivating participants through CSGs, only in the last few years has the CSG player's experience really been scrutinized. Ponti et al. [140] comparatively explored the players' experiences in Galaxy Zoo and Foldit and found several key themes, including: tensions between knowledge production and competition, frustrations as a result of gaming mechanics or practices, and questioning project goals. Eveleigh et al. [56] investigated the role of 'dabblers,' or casual contributors, in CSGs. Their findings supported Haythornthwaite's theory that intrinsically motivated volunteers are more likely to contribute in depth and form a community [79]. Moreover, their work highlights the importance of understanding and breaking down barriers to initial participation, such as by acknowledging contribution efforts, decreasing boredom, and enabling the players to fit the game around their existing schedules.

Díaz et al. [50] asked players directly about their game experiences. They found that players struggled to understand the game (Quantum Moves [92, 115]) and wanted better tutorials; as one player put it, "Both too simple tutorials and challenging game, too steep learning curve." Another expressed a desire for more scientific clarity, "Explain how the game works, make a link with the part of physics which it concerns, it was all a bit unclear what [it] is really all about. It worked for me but have not a clue what you accomplished with all data that is gathered. The idea to turn to the public is great, but explain more." The researchers concluded that providing tutorials could equip players with a better understanding of the game mechanics and increase participation and game interest. This desire for better tutorials was also found in a systematic literature review of citizen science volunteers more generally [170]. Volunteers asked for better tutorials, claiming that the help page and tutorials were among the least useful and least usable features (specifically, for iNaturalist), and several articles in the review discuss the need for providing tutorials in various forms.

So now we know what CSGs are, why they're useful, what motivates players to play them, and a bit on how the games themselves are experienced. And we also know — in broad strokes — how expertise is gained in games. But what we don't know is how expertise is gained in CSGs and, in particular, in ECCSGs where expertise is a crucial factor of the game's success and its scientific contributions. The players' journey to expertise is also an important part of the accessibility and inclusion of CSGs. We already know from previous studies that CSGs have participation biases based on age, gender, and scientific capital — the older Western males already rooted in scientific culture have much greater access to making and benefiting from citizen science contributions [171]. If ECCSGs were to introduce an additional cognitive constraint (which they do), accessibility and inclusion is further restricted. This work is not just about making learning easier, it's about the public's right to participate in the production and consumption of scientific knowledge.

In summary, there exists a gap in the literature in the systemic ways players are hindered or prevented from gaining expertise in ECCSGs, which is critical to the value of ECCSGs to make scientific contributions and engage the public in the production, organization, and circulation of scientific knowledge. This work seeks to empower CSG developers and their players to identify and overcome these barriers, lest the frustrations of expertise-centric CSGs disillusion the public and shy them away from a valuable form of citizen science.

2.4 ECCSGs

We have been talking about ECCSGs but have not yet discussed them in detail. The term ECCSG is as recent as 2018, describing citizen science games whose valuable output is not the problem being solved but the knowledge of how it was solved so that the knowledge can be organized, generalized, and shared [97]. For these games, Keep describes, knowledge sharing and organization are critical processes that require careful translation between the volunteer community and professional scientists. Closely related to ECCSGs is Schrier's notion of *knowledge games*, games that "seek to produce knowledge; solve authentic, applicable problems; or generate new ideas and possibilities for real-world change" [161].

For the purpose of this work, we define seven criteria of ECCSGs. This definition is also a contribution of the present work, as ECCSGs have not yet been defined this thoroughly. ECCSGs typically exhibit at least four of the following seven criteria[3] which exist on a qualitative spectrum (for example, an application can vary in its gamefulness). Each criterion will be more thoroughly discussed below.

An ECCSG: (1) is a game or gamified application; (2) requires / develops expertise; (3) makes citizen science contributions; (4) solves novel problems; (5) produces expertise intentionally; (6) produces expertise *concretely* (e.g., by sharing or documenting knowledge); (7) produces expertise *in a new domain of knowledge*. Examples of games and related concepts or genres which meet all or some of these criteria are summarized in Table 2. This table is by no means exhaustive or systematically-derived, but captures the most defining ECCSGs of the genre as well as much of the breadth in the gaming and citizen science circles which are closely related to ECCSGs.

Unpacking the ECCSG criteria and related concepts, most notable comparisons to ECCSGs tend to be games or gamified projects, including traditional (i.e., data-centric) CSGs,[4] citizen psych-science games,[5] and educational gaming.[6] For comparison, citizen science platforms such as Zooniverse [3] and iNaturalist [1] represent areas of citizen science which are not games, though some projects on these platforms are 'gamised' or gamified [57, 73].

The next two criteria are the most defining for expertise-centric citizen science games, namely the requirements of expertise and of citizen science contributions. Citizen science contributions are simple and objective in definition, and the only example listed that does

[3]Interestingly, at the time of writing no ECCSG strongly meets all seven criteria.
[4]Such as MalariaSpot [120], Project Discovery [111], Forgotten Island [145], Play to Cure: Genes in Space [35], and Phylo [96]. This category also includes most knowledge games [162], games with a purpose (GWAPs) [107], human computation games (HCGs) [93], and crowdsourcing games [120], such as SchoolLife, Specimen, The Restaurant Game, the SUDAN game, the ESP game, Which English?, Who is the Most Famous? (cf. [161, 162]), and VerbCorner [78].
[5]Citizen psych-science is a branch of citizen science wherein the scientific data of study is provided by players about themselves [90], such as in Skill Lab: Science Detective and Sea Hero Quest [85, 137].
[6]Including both educational games (such as DragonBox [169]) and gamified learning (such as Khan Academy [126]).

	ECCSGs			Related Concepts			
ECCSG Criteria	**Foldit, Eterna**	**Eyewire, Mozak**	**QM, QM2, Decodoku**	**Trad. CSGs**	**Cit. Psych-Sci. Games**	**Edu. Gaming**	**Cit. Sci. Platforms**
Game or gamified	✓	✓	✓	✓	✓	✓	Varies
Requires/develops expertise	✓	✓	✓			✓	Varies
Citizen science contributions	✓	✓	✓	✓	✓		✓
Solves novel problem	✓	✓	✓	Varies	Varies		Varies
Produces expertise intentionally	Partial		Varies			✓	
Produces expertise concretely	✓	Varies		Varies		✓	
Produces expertise in novel domain	✓		✓				

Table 2: A comparison of some ECCSGs and related concepts, with their relations to the ECCSG criteria. On the left are games which meet enough criteria to be considered ECCSGs. On the right are concepts and genres closely related to, but distinct from, ECCSGs. This table is meant to be illustrative rather than exhaustive, in order to provide positive and negative examples for each ECCSG criterion. Explanations for each row and column are provided in subsection 2.4.

not meet this criterion is educational gaming. For the criterion of expertise, however, definitions are more nebulous. We operationalize expertise by whether the tasks can be performed competently with very brief training (one could make a specification, such as 30 minutes, but the threshold is moot — data-centric projects are learnable on the order of minutes while expertise-centric projects are learnable on the order of days to years). For example, one of the tasks of iNaturalist is to record observations of flora and fauna and guess at their identifications. Although the guesswork may have elements of expertise, most laypersons can take and submit photos for meaningful contributions with only minimal instructions for taking clear shots of the subject and uploading photos. Similarly, most data-centric CSGs and citizen psych-science games are about providing and/or labeling data — through various means — which can be easily taught (e.g., MalariaSpot lists its entire instructions on one screen [120]; the Sea Hero Quest tutorial takes approximately four minutes [182]). Eterna, as a counter-example, lists an 84-page guide [129] among its 46 other player-made guides on the Eterna wiki [2]. At the time of writing, the Eterna tutorial[7] itself contains 118 levels and takes an average player at least 21 hours to complete (Personal communication, Eterna developer Jonathan Romano, Dec 2, 2021). In this way, expertise is related to *access to contribution*, defined by Rafner et al. [151] as "the likelihood that an average lay person (assuming there are no impediments to participation e.g. physical, socio-cultural, financial, or technological) would make a scientific contribution to the project" — thus, we argue that expertise constitutes a cognitive and temporal barrier to access; the greater the required expertise, the more difficult it is to contribute.

Regarding novel problem solving, this criterion excludes projects which train expertise for the sake of training (novices, AI, etc.) rather than for the sake of new knowledge. For example, educational games are not solving new problems but rather teaching new students about old problems. Similarly, citizen science games which focus on natural language processing (such as VerbCorner, a gamification of labeling verb usage in order to improve the existing VerbNet database [78]) ask players simple questions about natural language. Although the content of the question may be novel, the task is not. In Foldit [40], on the other hand, players are designing novel protein sequences through a system of manual manipulations unique to Foldit — not even professional biochemistry scientists use this particular workflow [41, 103], and it is possible for an individual player to single-handedly design novel proteins.

Most citizen science and citizen psych-science games, however, fall somewhere in the middle with respect to the novelty of the problem. Games in these categories are often about contributing data to a larger dataset in order to collectively solve a novel problem, such as Phylo's attempts to solve the Multiple Sequence Alignment problem [96]. In this way, these games tackle novel problems by applying machine learning — or sheer amounts of data — to answer a yet unanswered question, though the novelty of the task itself varies.

The final three criteria refine the definition of an ECCSG. To our understanding, there is only one ECCSG to have ever existed which strongly meets the criterion of producing expertise intentionally: Decodoku [199]. In Decodoku, researchers explicitly collected no data except the player strategies via written reports to the scientists [198, 199]. Unfortunately, Decodoku had a small audience and is no longer available, which is why it was excluded from the present study.

Foldit, Eterna, and Quantum Moves (QM) [115] (and its sequel, Quantum Moves 2 [92]) come the second closest to intentionally producing expertise. Their intentions are instead in hybrid intelligence, best phrased by Lieberoth et al. [115, p. 222]: "The aim of

[7]For this article, "tutorials" refer only to developer-made or officially recognized tutorials. Only one CSG known to the authors (Eterna) has player-made tutorials and they did not significantly impact the themes discussed in this study, though the concept warrants further investigation.

Quantum Moves is to combine the best of both worlds in our gamified human quantum optimization: optimization that is rational most of the time, but sometimes makes seemingly random errors or leaps of intuition to rapidly find the sought after solutions." In this way, while these games aim to combine human intuition with computational optimization, there is no explicit intention to harness expertise, for example by codifying player-made strategies with the intention to design new algorithms, although some literature touches briefly on the potential to do this [99, 109].

Next, an ECCSG produces expertise concretely, that is to say, in a way which records the expertise by means of sharing, documenting, and organizing the knowledge. Although both Decodoku and Quantum Moves seek to understand the problem-solving process, there is no public evidence of expertise-formation — they are single-player games, and only the developers have access to the gameplay logs and player reports [115, 198, 199]. Comparatively, Foldit, Eterna, and Eyewire are very social games which have extensive player-guides and player-made wikis[8] that continuously update the shared body of knowledge which the players have developed and organized about how to solve the game's problems. Importantly, this is the only ECCSG criterion which distinguishes traditional CSGs, which can be deeply social projects that encourage domain knowledge sharing and organization, from citizen psych-science games, which are inherently about individuals and thus cannot have a similar body of knowledge [43, 90].

Finally, an ECCSG produces novel expertise. That is, the expertise that the players develop is a new form of expertise, often complementary to that of the professional scientists who develop the ECCSG but distinct from the scientists' domain. As an example, the Eterna player community has developed an entire vocabulary around the idea of "boosting," which is a community-made strategy (unique to Eterna players) for stabilizing RNA sequence stems with specific base pair mutations [53]. To employ Gee's Discourse theory [65], the players developed a novel Discourse, complete with its own semiotic domain and highly specific and functional language. Contrast this with learning about RNA in the first place. Eterna players must also learn this rather niche knowledge, but details about nucleotide sequencing, the different types of RNA bases, and other declarative expertise is also shared with the scientists who built and run Eterna. In this way, Eterna can be considered a boundary object [112]: an ill-structured set of work arrangements adapted by two groups cooperating — without a shared definition — as they move between the object's identities and forms.

With these seven criteria laid out, readers may be wondering what types of problems are good candidates for ECCSGs — what are the inherent aspects of a problem which suggest the affordances of ECCSGs? We can determine this by reversing our definition and asking what the affordances are of the ECCSG criteria. Games and gamification afford, among many other properties, self-containment (barring manuals, wikis, etc., games are a closed loop), interactivity (especially system interaction) and motivation to engage in the activity (even to the extent of obsessive passion) [6, 48, 121, 193]. Expertise affords solving complex problems; citizen science affords the collaboration of thousands of laypersons and scientists; and so on. The resulting set of affordances suggests problems which ask a crowd of players to thoroughly explore a system or problem space and become scientists and experts in their own right. The resulting player experience is reminiscent of Alternate Reality Games (ARGs), which often have incredibly complicated problems and require the collaboration of thousands of players across the globe [15, 101] — the difference being that ECCSGs tackle real subject matter. To phrase succinctly, **ECCSGs are best suited to address system-driven, self-contained, complex problem spaces with many problems to solve**. With these affordances unpacked, we can hypothesize about future ECCSGs that could exist, for example: a game where players succeed by developing increasingly more efficient machine learning algorithms with novel constraints; a game about testing novel agricultural techniques in a simulated environment; or the gamification of translating a dead language or dialect that few people are familiar with.

Now that we have defined ECCSGs, we return to the present study to understand the barriers to gaining expertise in ECCSGs.

3 METHODS

Methods were approved by the institutional review board at the authors' institution. The three games examined were Foldit[9] [40], Eterna[10] [109], and Eyewire[11] [178]. As shown in Table 2, there are only a few games (to our knowledge) currently available meeting enough criteria to be considered ECCSGs. For the purpose of this study, we focused on ECCSGs that produce expertise concretely, since the organization of knowledge is a key component to understanding expertise-formation. This inclusion criteria helped us become familiar with the games studied and framed experts' input in a larger body of knowledge, allowing us to better analyze and thematize results. We also excluded games that are no longer available, namely Decodoku. A study of games with less concretely published expertise (Mozak, Quantum Moves, and potentially other games we are unaware of) is left as future work.

3.1 Descriptions of Games Studied

All three games studied are difficult puzzle games. In Foldit, players attempt to fold a protein in 3D space via spatial manipulation using a variety of gameful tools and algorithms such as "wiggle," a local optimizer [40]. In Eterna, players edit the base pair sequence of a 2D RNA structure to match a target structure. Both games feature structure design, sequence mutation, and programmable scripts that allow custom combinations of actions. In Eyewire, players are tasked with reconstructing a 3D model of a neuron based on 2D slices of data from serial electron microscopy images [102]. Their success is measured based on input from other players and an initial task-assignment seed from a convolutional neural network [110, 122].

3.2 Participants and Protocol

Purposive sampling was used to recruit ECCSG players (n=16: 12 Foldit; 3 Eterna; 1 Eyewire) — via game website messaging systems — from diverse backgrounds of expertise ranging from very novice to

[8] See https://foldit.fandom.com/wiki/Foldit_Wiki, http://eternawiki.org/wiki/index.php5/Main_Page, and https://wiki.eyewire.org/Main_Page

[9] https://fold.it/

[10] https://eternagame.org/

[11] https://eyewire.org/

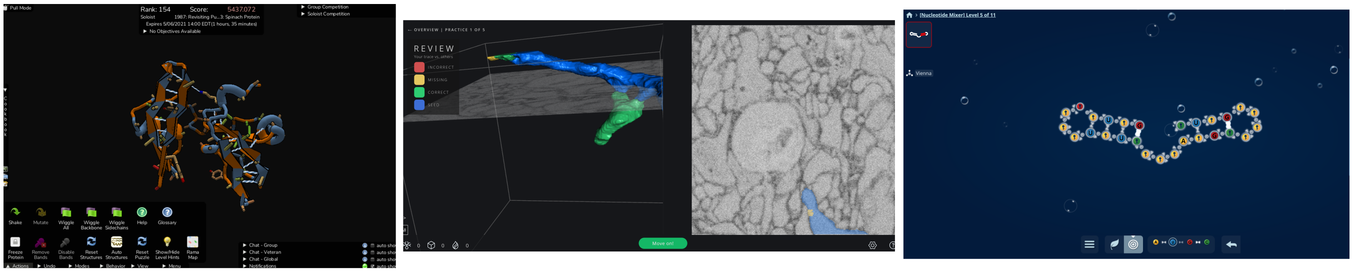

Figure 1: Games studied: Foldit (Left), Eyewire (Center), and Eterna (Right). Screenshots taken by the first author.

extremely expert. This size was found to be pragmatically sufficient (cf. "saturated" [22, 74]), pragmatism being a recent heuristic to address the problems with defining theoretical saturation as "no new information" from a qualitative analysis; instead, we let go of the notion that research would ever lead to a definitive stopping point and instead stop data collection based on practical constraints while still ensuring our analysis forms a coherent conceptual model [22, 119].

The skew toward Foldit exists for three reasons: first, this sample is proportional to the community size for each game — Foldit's active player base is several times that of Eterna's and Eyewire's.[12] Second, the authors — being Foldit developers ourselves — have more experience with Foldit and can better analyze player descriptions of expertise. Third, prior literature has more thoroughly investigated Foldit (as a game), so there are more points of reference for comparison (e.g., [4, 39, 43, 60, 98, 140, 141]). Moreover, our analysis focused only on phenomena represented across all games, with the exception of subsection 4.4.3 which has been found previously by Ponti et al. [140] and is described here for the purpose of connecting their result to a broader dilemma in ECCSGs.

No other demographic data (e.g., age, gender) were collected. This was both to protect our participants' anonymity and because expertise is not causally linked with these variables. However, some of our participants have publicly released information about themselves via in-game profile pages, and based on these data we believe our sample to be an accurate representation of typical CSG populations [44]. Further, we cannot provide clear measures of expertise because each player's experiences vary. For example, some players have played on and off for several years and were unable to recall exactly how much experience they have, in terms of months' experience or hours played. Instead, we allowed players to self-report expertise and collected experience reports where available. We found that players generally self-reported as novices at less than 2 years of experience, intermediate at 2-5 years of experience, and expert at more than five years of experience. Therefore, we use this heuristic combined with self-reports when describing players quoted in this article. This categorization resulted in 3 novices, 9 intermediates, and 4 experts.

Participants were interviewed online for about an hour in a semi-structured format about their play experiences, their skills in the game, and how they conceptualize those skills. For example, some questions asked were "What is the very first skill a player needs to learn in [game]?" and "How is the process of becoming skilled in [game] similar and different to becoming skilled in [other games or other hobbies they feel skilled in]?" Other questions included asking about the visual cues for expertise, how the player would hypothetically redo the tutorials with an infinite budget, what they wish they knew when they first started playing, etc. Participants were then offered a $15 USD Amazon gift card as remuneration. The interviews were audio-recorded and then transcribed for further analysis. In total, 16.2 hours (per participant: M=60.75 minutes, SD=11.86) of data were collected.

3.3 Analysis

Data were analyzed using reflexive thematic analysis conducted by the first author in order to take a "Big Q" [100] qualitative approach to our research question [20, 21]. The use of a fully qualitative research method is required here because: (1) our target population is small, so quantitative methods would be impractical; (2) positivist measures of expertise across a range of domains (different games) would struggle to make meaningful comparisons between domains; and (3) the nature of our research topic (gameplay and player experience) is strongly subjective. Moreover, we were not interested in a close analysis of language use (which would suggest interpretive phenomenological analysis or discourse analysis) or a post-positivist content analysis (and related "little q" codebook approaches), and our sample is too small and homogeneous for grounded theory, making reflexive thematic analysis the optimal choice for our goals and constraints [23].

The analysis approach was primarily deductive, latent, and constructionist. We theoretically grounded the analysis in constructivist and constructionist theories of learning and play (i.e., games as constructionist learning environments [48], play as constructing predictive mental models [5], and games as constructivist affinity spaces [68, 163]) and aimed to answer our research question: "What is the path to expertise in ECCSGs and what are the major barriers along that path?" We additionally took a critical orientation to sense-making, but we included an element of critical realism in that we were open to the data providing evidence against our assumption that player experiences are explainable by our theoretical framework. Therefore, we code both for semantic and latent meaning in order to capture the overt player experiences as well as how these experiences might be interpreted through our theoretical lens.

[12] Estimated based on media reports of registered players [18, 175, 183], game community activity (e.g., Discord), and personal experiences in each game's chat room during the time of writing.

The analysis occurred in six rounds of iteratively passing through the data to apply codes, merge codes into themes, and return to the data to validate and refine themes. As stated above, codes were both semantic (e.g., "uses Wikipedia") and latent (e.g., "exploratory learning"). During the initial coding, all codes were unique and descriptive. Subsequent rounds of coding then oscillated between aggregating codes by similarity and verifying the new codes were still accurate to the original transcription. By the fourth iteration, codes were aggregated enough to be representable as themes which were then refined over two additional rounds of analysis. In order to minimize the effect of the skew toward Foldit's population, special attention was given to ensure that themes were grounded in data from participants of all games and not found only from Foldit players. Note also that the analyst is himself a Foldit developer; although this imparts a kind of bias to the research, it also uniquely positions us to understand the situation from both the player and developer perspectives. And, as stated earlier, emphasis was placed on ensuring themes generated were evidenced across all games to reduce bias toward Foldit. For validation of our methodology and future research, an audit trail and additional quotations are provided at: https://osf.io/hn7x2/.[13]

Finally, after themes had been generated, the participants were consulted again for transparency — to verify that the results below accurately represent their beliefs and experiences. This check was performed in case the researchers had misunderstood or misquoted the participant, or changed their meaning by taking a quote out of context; this resulted in one quote being clarified but did not affect the themes generated.

3.3.1 Reflexivity and Positionality Statement. In recognition of the sociocultural issues surrounding human-computer interaction research — in this case especially, regarding questions of accessibility and inclusion to science culture — we believe it is important to acknowledge the inescapable bias of our personal position from which we approached our participants and analyzed their data [114]. We come from an affluent Western culture and are immersed in science and gaming culture, thus giving us a wealth of science capital [7] and biases toward gaming norms. Moreover, we are Foldit developers ourselves, which influences the way our participants see us; however, the interviewer approached Foldit participants as a researcher rather than a developer and encouraged open, critical feedback.

4 RESULTS

The results of the analysis are shown visually in Figure 2. The path to expertise was found to be a cycle of exploratory learning followed by social learning with three major barriers along that route: onboarding and continual learning carry the instructional barrier of Missing Instruction, then exploratory learning is hindered by a host of game-related barriers wherein Missing Polish causes friction with the game interactions, and finally social learning is blocked by Missing Communication, the sociocultural barriers. The remainder of this section unpacks each of the four themes (path and three barriers) in subsections.

[13]For privacy, please contact the first author for access to anonymized transcripts.

4.1 The Path to Expertise is Social and Exploratory

One major question of this research was "What is the path to expertise in ECCSGs?" This question is perhaps answered most succinctly by P11:

> *It's a combination of, like, messing around and then looking it up somewhere else and asking somebody.*[14] (P11, Foldit, Intermediate)

In this way, player learning is both constructionist and constructivist. They first explore, constructing their own mental models, and then exchange tangible artifacts (i.e., puzzles and solutions) and ideas as a community, building a collective knowledge base which iteratively informs further exploration. Notably, as shown in Figure 2, the order is important. Players highlight that in this cycle of explore-discuss, experimentation comes before learning in order for the problem space to become meaningful:

> *I have to struggle with it before it has any meaning to me to look it up online. Like I could just look it up online, go, oh, look at the perfect thing. But it doesn't have as much meaning to me unless I sit there and poke at it for half an hour and then look it up.* (P5, Foldit, Novice)

Compare this to Schwartz's and Bransford's "time for telling" [164], the notion that students require the time and space to discover a problem and its significance before being told the solution(s). In line with constructivist learning, players are grappling with a problem before being ready to understand ways to solve it. They are experimenting and engaging in trial-and-error discovery learning. P9 (Foldit, Expert) describes she would "consciously set goals for myself... I was actively experimenting with stuff... I was ... actively chasing this knowledge."

However, the "time for telling" approach works best as guided discovery or scaffolded inquiry, rather than unconstrained discovery [25, 34, 164]. What the players described was very much unconstrained, unguided, and unscaffolded, suggesting that the value of experiential learning may be an artifact of the currently available guidance for players. "Most of the expertise that you need to operate the game do not appear in the tutorial," says P13 (Eyewire, Intermediate). "They are gained from experience and trial-and-error."

In this way, the game effectively forces players to learn by experimentation because no other option is provided. If the game were better scaffolded through carefully crafted instructional design (e.g., following Quintana et al.'s scaffolding framework [149]), would this learning path still be relevant? Minecraft, for example, began with a similarly unguided social-exploratory onboarding experience, but as its Education Edition has grown in popularity, there are now over 600 guided lesson plans for teaching Minecraft and teaching with Minecraft [11, 106].

Complementing the exploratory, the other half of the path to expertise was social. Across all three games, players consistently emphasized the role of social learning as deeply embedded in their path to expertise. P3 (Foldit, Expert) emphasized socialization, team connections, and community as fundamental to his experiences. As one example, he praises the asynchronous cooperation of being able

[14]Some quotations are abridged for readability.

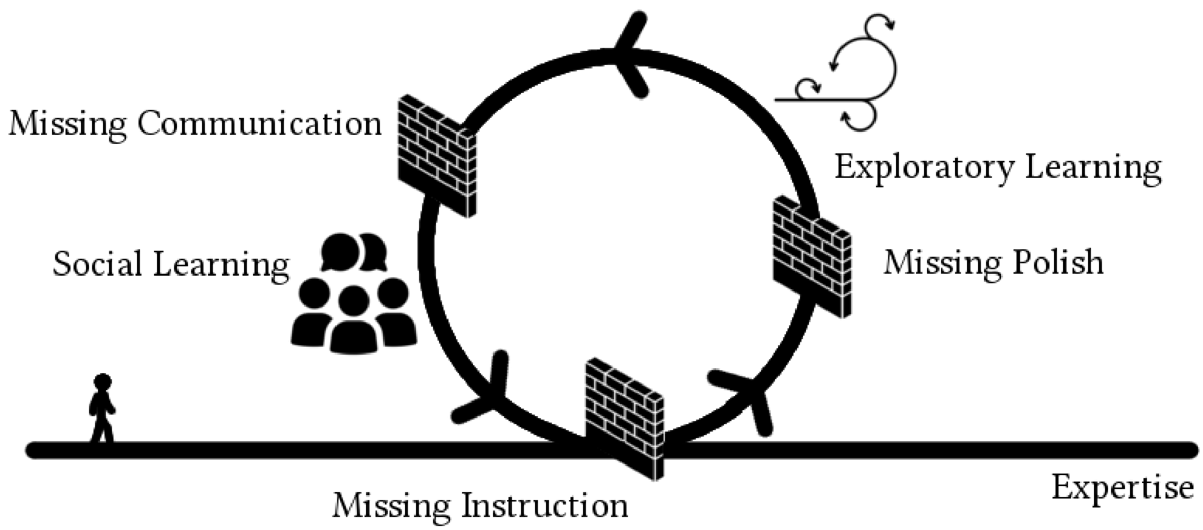

Figure 2: A visual representation of the main themes generated from the reflexive thematic analysis. The path to expertise is a cycle of exploratory and social learning with three barriers: Missing Instruction, Missing Polish, and Missing Communication. Icons licensed under Creative Commons from the Noun Project: Social by Adrien Coquet; iterate by Justin Blake; brick wall by Bakunetsu Kaito.

to "hand off" his work in the evening to a teammate halfway around the world who was just waking up and could continue his efforts. Additionally, the community acts as a collective source of knowledge and motivation. "There's a community of veterans that you're stepping into who can share information and encouragement," says P9 (Foldit, Expert).

This constructivist learning is bolstered by several forms of peer learning that the players described, including peer modeling, peer tutoring, and peer assessment [71, 179]. Through this social engagement, players form lasting relationships with each other that extend beyond aspects of teaching and learning:

> *[The process of gaining expertise] more and more relates to how it connects to players that eventually helped. And what's most important to me was the people I eventually found that, you know, that you build a relationship with and you build trust in and you really respect around the issues of science.* (P14, Eterna, Intermediate)

To use the language of Gee's Discourse analysis [65], these tight relationships eventually become portals to the semiotic social space or affinity space [67] — in other words, player relationships create entry points into connecting with scientific issues and assimilating into such a community. While the game generates the explorable space, veteran players act as portals for new players to enter and assimilate into that space.

To summarize, the path to expertise is currently a cycle of experimenting and discovering via social learning and the use of paratexts [37] such as guides and wikis to "look it up" (P5 and P11). There are several noteworthy comparisons between this and Jennett et al.'s MLC model of engagement and participation [91].

Jennett et al. use the language of "micro" and "macro" tasks (calling back the Gaming Involvement and Informal Learning framework [89] and the Player Involvement Model [27]) to speak of the in-game, moment-to-moment play as the micro-involvement and the external, surrounding, or off-line activities as the macro-involvement. Using this language, then, we claim that expertise is a cycle of micro and macro involvement in that order: interactions with the game itself (Gee's "generator" [67]) triggers interest in socializing and the use of paratexts external to the game ("portals"). Engaging externally then informs later play, giving the player newfound language and ideas for interaction, and thus placing the media object itself at the center of this "big D" Discourse [69]. Jennett et al. observed this learning as well, though not with the sequential distinction we place on it now: they found that participants learn by the micro-involvement of contributing and the macro-involvements of interacting with others, using external resources and project documentation (paratexts), and sharing personal creations (such as creating their own guides) [91].

However, neither halves of this cycle speak to *why* players engage with the game. Although — as noted in Section 2 — much is known about CSG motivations, we sought to verify if these motivations hold true in the context of expertise-centric play. Based on player input, we argue that engagement has dual drivers: the scientific value and self-gain. This expands on previous work, which describes the motivations of "altruistic factors" (e.g., [43, 150]) or "personally-focused reasons" (e.g. [8, 155]) [9, p. 247], to specify that something from each of these motivation categories is required for continued play.

Some players began play for the scientific contributions; others began for themselves, such as for entertaining gameplay or personal learning. But for those who have reached expertise, it becomes clear that both motivations are required for expertise: one needs to be invested both in the science and their own benefit to continue playing:

> *The chance to both do hard puzzles and contribute to science. It's really what got me interested and what has kept me interested.* (P9, Foldit, Expert)

Although not a requirement, the most common form of self-gain was intellectual challenge:

> *I've been looking for something intellectually challenging to get involved with that I find interesting... I have a pretty strong science background from college that I never really used but I'm a bit of a science geek. So that was very exciting: the idea of designing RNAs and having them synthesized and tested in a lab was very exciting.* (P16, Eterna, Intermediate)

Most likely, the skew toward intellectual challenge is because all existing ECCSGs fall within the puzzle genre. This may not generalize, since there is nothing in the definition of ECCSGs which requires them to be puzzle games. This finding is consistent with previous research on the motivations in CSGs which state that players are drawn into CSGs by their previous interests in science, the specific research topic, curiosity, and a desire to contribute to research, and their continued engagement is dependent on intrinsic enjoyment, proper pacing, teamwork, community, and intellectual challenge [43, 88, 91, 177].

Another key aspect in the path to expertise is the development of what Goodwin refers to as a "professional vision" [72]. This is not a new finding, as Ponti et al. [141] discovered this several years ago in Foldit. However, the present study confirms that expert players of all three games studied describe recognition, both of the problem space and solution space, as a critical skill of expertise and a factor of decision-making. Some Foldit players describe this professional vision as an aesthetic intuition:

> *I call it a protein aesthetic. I think after you play with it for a long time, you get a sense of what looks good. Y'know when we chat with each other in group, we'll say "that looks beautiful." And what we mean is it conforms to how we have come [to know how] proteins [look] when they're correctly folded.* (P3, Foldit, Expert)

In fact, this professional vision is so ingrained, so intuitive, that participants struggled to talk about their expertise and learning process, which is perhaps an obvious finding for researchers familiar with cognitive task analysis (CTA). As CTA researcher Clark writes, "experts don't know what [others] don't know," in other words, experts significantly distort or omit details of their own expertise without specialized knowledge probing [33]. P12 (Foldit, Intermediate) says that they "can't really put into words what makes a well-designed protein." P7 (Foldit, Intermediate) describes it as feeling like he is a neural network and not being able to describe his own weights and biases: "It's intuition for me. It's more just like deep understanding... I don't know, I'm describing how to, to do 2+2 is 4, it's strange."

Novice ECCSG players also recognize that this intuition is one of the core elements of expertise in the game:

> *The peak performance play is when you know that something is in the wrong place or in the wrong shape and you can try to impose your will into the game.* (P8, Foldit, Novice)

Moreover, our study confirms that this phenomenon extends beyond Foldit. Eyewire and Eterna players also described having a professional vision, using much the same language as Foldit players. P13 (Eyewire, Intermediate) says that working with difficult data in Eyewire involves "knowing how a cell is supposed to look."

Similar to other domains of expertise, we observe that ECCSG experts "see" the domain space differently, using unconscious structural heuristics to guide problem-solving [29, 31]. Identifying this professional vision is critical in light of Keep's philosophy on ECCSGs: because the value of these games is the expertise itself, rather than the problems solved by expert players, it is absolutely necessary that developers provide support for documenting, sharing, and organizing their expertise [97]. Without developer assistance, players will struggle to articulate their own learning and knowledge. Even in successful examples of social learning in games, much of the knowledge is "impenetrable" without first spending time submerging oneself in the game experience and the online community [172].

4.1.1 The Role of Science Knowledge. Because ECCSGs involve scientific domain knowledge, we also sought to explore how knowledge of the relevant scientific topic connects with expertise in the game. Is it a barrier to expertise, a necessary component on the path to expertise, or something entirely tangential and parallel to game expertise? Interestingly, we found that the role of science knowledge was different for each participant. This may signal that there is another theme to be explored here as future work. Given our sparsity of data, we draw no substantial conclusions, but offer several perspectives. These perspectives can be seen as forming a spectrum, from science having no connection to the game to the two being integrally linked. The first perspective, offered in third-person, is that the science is irrelevant, most players simply want to play a game:

> *Our current two labs we have going on are very science heavy and I think there's some players who don't like that. I think the majority of players, they like having that wall there. "Just give me a game to play." And... They want us, they want the advanced players and the developers to create the definitions, to understand the science and create the definitions and say "here, we need you to solve this as a puzzle." And, having too much science involved, they don't want to read it. They don't want to read it. They come on to have fun for an hour. They don't want to be reading

> *about science, they don't want to be reading. So I think there's an ongoing debate about how much science to provide to most players, whether they want it or not. Whether they* need *it or not. And I don't know what direction it's going to go in and which is best.* (P16, Eterna, Intermediate)

The second perspective is that the science is important, but actively learning the science is not necessary because it's intrinsically embedded into the gameplay:

> *[Learning the science] kind of just happens naturally because the metagame in Foldit is inextricably linked to the actual physical science of good protein folding.* (P1, Foldit, Intermediate)

The third perspective is that you don't need to learn the science to play, but you do need to learn it to play well:

> *It was said that basically you don't have to know anything about organic chemistry or, you know, or molecular chemistry... in order to do these. And my answer to that would be, yes, that's true. But if you want to do those puzzles and do well at those puzzles, I believe that you really have to know something. I mean, to me, it's like, sort of like playing chess. You know, anyone can learn the rules and move the pieces [but] to be an expert chess player, you know, it's going to take years and years of studying. And so I feel honestly that a person who has taken chemistry courses or biology courses or whatever, you know, I think that they're probably in a much better position to do those puzzles.* (P6, Foldit, Novice)

Finally, the fourth perspective is that the science is critical to motivating play, and in fact the most difficult part of onboarding:

> *I think I struggled the most with my own knowledge and to get the knowledge I have now, this was the hardest part, I think. And if I wouldn't be interested in protein design or biochemistry, I don't know if I would have kept playing... Be interested and get the knowledge, that was the hardest part, I think.* (P10, Foldit, Intermediate)

Despite this open question of whether all players need to learn the science, it seems that at least some players need to know the science so that there can be a bridge in communication between scientists and players. P16 (Eterna, Intermediate) describes another player who "is invaluable because he is a player and he understands the player perspective, but he also understands a lot of the science, and the scientists, and how they think." Player-scientist communication will be further unpacked in Section 4.4 as participants describe how science jargon is one of the major barriers to understanding their contributions and how to play.

This finding is most easily interpreted through Harteveld's Triadic Game Design framework, which posits that serious games are a confluence of three interconnected components: reality (e.g., protein design for Foldit), meaning (in ECCSGs, learning and scientific contribution), and play [77]. The value of this model is that it allows us to view design issues as problems within each 'world' ("tensions") and at the intersections between them ("dilemmas"). Specifically, the role of scientific knowledge is offered here as a 'trilemma' of ECCSGs, a tension from the interplay of all three aspects of citizen science gaming. What role does science knowledge play within the game, and how can scientists and developers teach it? It is clear that the scientific topic is, in some way, connected to the gameplay. But is it a requirement, a distraction, or altogether parallel? The answer is most likely that it plays different roles for different players, depending on their prior knowledge and interests. And if so, how can scientists and developers handle the science differentially for each player? This paradigm would seem to require CSGs to both teach the science effectively and let it go ignored should the player choose. Currently, neither goal seems to be satisfied, given player frustrations from each side.

To summarize, we found that the path to expertise is: (1) built on constructionist (exploratory) and constructivist (social) learning, (2) requires both motivations from scientific contribution and self-gain, and (3) involves the development of a professional vision; points 1 and 2 are novel contributions of this study while point 3 is a confirmation and extension of previous work [141]. With the path to expertise defined, we generated three themes to identify the barriers along that path. The first barrier encountered is Missing Instruction as the players are onboarded. Then they experience the friction of Missing Polish while exploring the game and the barriers of Missing Communication while seeking social assistance.

4.2 Missing Instruction (The Instructional Barriers)

As described in the previous section, although the path to expertise was found to be social and exploratory, this may be because the games themselves were insufficient at providing instruction. Perhaps the largest barrier of all, participants described an incredibly steep learning curve for all three games, which is likely an important factor in player retention and churn. This steep learning curve comes in part from a lack of guidance (see also, unclear gameplay in Section 4.3):

> *You had no advice from any tips or stuff like this, how to start... with a long strand of amino acids? Yeah, just "Go for it. Build a protein." And I didn't know where to start, how to improve a structure, what was a stable structure for a given [sequence of] amino acids.* (P10, Foldit, Intermediate)

Not only is the learning curve steep, it also tends to be long. P2 (Foldit, Expert) claims the average duration required to understand Foldit is two years. If the learning curve in practice is anywhere close to this length, then learning how to play the game is creating a significant lag for scientific progress in ECCSGs. One Eterna player describes in detail how the tutorials were simultaneously too difficult and unhelpful — so much so that she felt at first as if the developers were intentionally trying to gate-keep players from contributing to the science of the game:

> *It was very difficult. There [were] a lot of concepts to learn, and I found I did best by doing an hour a day. I didn't know any of the concepts, so I had to learn it all and let it sink in. So I had to learn the concepts. It's a lot to learn to take in — and you*

> *have to learn 'em, there's no other way around it. You just have to learn 'em. And then several of the puzzles, the tutorial[s] were really too hard and there wasn't any benefit to 'em. They were, I felt they were more challenging the critical thinking skills and trying to see, well, are you actually smart enough to solve all these hard puzzles or else we're not going to let you in. So to me... they made it challenging on purpose to try to reach the people who were really smart. Some of the puzzles were really hard. It took a couple, several hours to figure out. And I think they're going to change that, so I don't think that's the intention... So I felt some of the puzzles were too hard for no reason. But. I learned what I needed to learn in the puzzle and the puzzle progression. But it took me [[pause]] 40 to 80 hours, somewhere in there, a* long *time, and there's very few people who would dedicate that kind of time to learn the concepts if we're playing a game. And I try to tell them that... They never really believe me. I think they think it's much faster, the progression, than it is.* (P16, Eterna, Intermediate)

The other point that P16 makes is that players expect the learning curve to be shorter. Indeed, if the road to making scientific contributions is gated with such a steep, long learning curve, then ECCSGs raise the question of who is allowed to contribute to and benefit from scientific knowledge production [97]. One case study on the citizen science project *Supernova Hunters*, for example, created a bias of participation based on when datasets were released for volunteer effort [171]. In this way, project logistics may accidentally create accessibility barriers for those with less time or availability to contribute. Similarly, the skill barrier of ECCSGs forces volunteers to deeply engage to be allowed to participate, despite the fact that most members of the public don't have the resources to commit to such a deep engagement [97]. Participation biases strongly toward older (68% over the age of 40) males (as much as 78% in Foldit) from Western countries, as found in a survey paper by Curtis [44]. She also notes that many citizen science projects are biased toward appealing to participants with more *science capital* [7], or cultural and social capital related to science, such as scientific literacy, consumption of science-related media, and more opportunities to engage with science culture.

Given the required expertise of ECCSGs, there are two ways to lower this skill barrier: either the projects must recruit only volunteers with existing expertise (see The Argus Project [62] and The Polymath Project [42]) or make expertise accessible to all volunteers in a just and inclusive way. The latter approach may be why data-centric CSGs are designed to have a low skill floor — by reducing the skill barrier, the project becomes more accessible [97]. Ponti et al. similarly compare Galaxy Zoo, which emphasizes equality, to Foldit, which emphasizes meritocracy [140]. Their analysis of forum posts suggests that a project's framing can shape the community's ideals of science and views toward participation and accessibility, notably highlighting the community sense that Foldit seems "constrained," "closed and uncertain," and lacking Galaxy Zoo's spirit of belonging and collective contribution.

In addition to the entry barrier, ECCSGs fail to provide feedback on the players' work and overall progress. This challenge was clear in all three games, which require creative and complex solutions but do little to help the player iterate and improve their work. "At some point... I just can't advance any further," says P6 (Foldit, Novice), "I just have no idea of what to do at this point."

Instructional design theory suggests that both cognitive and corrective feedback is critical to learning [188]. Moreover, nearly by definition games require feedback to complete the user-system interaction loop by providing a "quantifiable outcome" [159]. Although these games have some feedback, it is insufficient for the player to make meaningful behavioral adjustments, thus calling into question whether the player can be gamefully attached to the outcome at all [94]. As P1 (Foldit, Intermediate) describes, "Foldit will grade you quantitatively, but it won't grade you qualitatively. And that's huge. I think that's huge. You'd need other players to help you out there." Because the game fails to give feedback, players need to seek it out from each other. This can add social pressures, especially for novices who are not yet comfortable engaging with the community. P8 elaborates on this tension of wanting more thorough feedback but being afraid of judgment and criticism from the community:

> *...You don't want to, like, put yourself on blast [i.e., embarrass yourself] ... go on the Discord server and say, "hey look at this thing that I created." Where it's a lot easier to passively absorb [other community interactions and community content]. I just sort of observe what other people succeeded with and just try to passively copy that off rather than sort of opening yourself up to... "Well, no, that's not the best way to do it." ... You know, you have to sort to put yourself out there in order to receive feedback in the first place where you could just say, "well, I could just avoid that all together."* (P8, Foldit, Novice)

Not only is there a lack of feedback on the player's attempts at solving a puzzle, there is also a lack of feedback on what these solutions mean in the broader context of scientific contributions. P9 (Foldit, Expert) notes that one of the common questions they see from players is: "am I really contributing?" As will be elaborated in Section 4.3, this connects to an unclear and often opaque loop between gameplay and scientific progress. Because there is no in-game feedback on scientific contributions, and rarely any external feedback on broader scientific achievements, players have no indication as to whether they are helping, which is one of the critical motivators for retention [91]. The motivational impact of scientific feedback and recognition was also found by Eveleigh et al. [56]. As one of their participants describes, "I lost motivation to continue contributing information because I was not sure how useful my input was." Indeed, based on Juul's definition of a game [94], players must be attached to the outcome: are CSGs still a game if the outcome is never made known to the player?

This issue also speaks to the broader problem of instruction: a lack of clarity on the elements and goals of the game. Part of why the learning curve is so steep is that the tutorials fail to answer "What am I looking at?" and "Why am I doing this?".

> *I'm not sure how this simulation relates to actually putting stuff in a jar and adding whatever. Like I said, I don't quite know. I'm sure there's a whole complicated process where they can actually make these molecules in real life. But it seems very far away from the game.* (P5, Foldit, Novice)

Although these are citizen science games, the actual science is disconnected from the game itself. As noted in previous work on breakdowns, involvement in a game requires the player to believe they are making a meaningful impact on the game world [86, 87]. When applied to citizen science games, the scope of the game world extends beyond the game to a real scientific laboratory. We can thus infer that player involvement further requires the belief of making a meaningful real-world impact. A lack of feedback on what the player is doing and how it relates in-game score and progress to real-world progress is therefore detrimental to the player's sense of involvement. The game elements, without context, become extraneous:

> *When I started playing Foldit, I just saw a score, but I didn't know what the score was... In the tutorials you see, OK, if you turn this amino acid to the right you get a higher score. But why? This was not so clear for me.* (P10, Foldit, Intermediate)

When scientists *are* able to provide meaningful feedback, it is met with joy from the players. During the COVID-19 pandemic, Foldit released several puzzles related to the novel coronavirus and provided extra feedback on lab results regarding them. P9 was delighted by this and describes how she wishes scientific feedback always came that often:

> *I'm frustrated by how slow science is... [Interviewer: Slow in what way?] To hear any results. Every time [Foldit] posts a video or a blog or anything that says "These solutions look good, here's some problems with those."* I love *that. Like "Oh, finally. Thank you! I needed some feedback," you know, and I think that, I think the community would thrive on just as much of that as you guys would give us. The fact that the Coronavirus feedback is coming so soon after the puzzle closes is* fabulous. *I* love *that. I wish that would* always *happen.* (P9, Foldit, Expert)

In addition to a high entry barrier and lack of feedback, there is a throughline running across both of these: the instruction of these games is missing the bigger picture. The tutorials teach the "micro tasks" but leave unanswered questions of "what am I looking at? And what are the little goals that go with looking at those things?" As P9 (Foldit, Expert) explains, "When you're in the tutorials, you have no idea what the macro tasks are."

The utterance of a "macro task" suggests that the best theoretical lens for understanding this player's experience lies in instructional design, specifically Reigeluth's elaboration theory, which posits that teaching is more effective when focus is given to the high-level concept between periods of elaboration on sub-concepts [154]. Similarly, van Merriënboer's Four-Component Instructional Design (4C/ID) model [185–190] gives focus to whole tasks, or the "macro" tasks that P9 describes. The 4C/ID model in particular is designed for complex learning, befitting ECCSG domains. Thus, according to P9, Foldit fails to stress the importance of whole tasks, teaching only basic controls through part-task practice and never orienting the player to the actual scientific challenges that they will be expected to complete. Indeed, whole-task-oriented approaches appear to be far more effective (for cognitively complex skills like ECCSGs) than the isolating alternative [116, 187].

Finally, for intermediate players the biggest barrier is that these games fail to teach key concepts required for expert play. While the tutorials may adequately cover some basic control schemes, they fail to introduce advanced concepts that are considered integral for actually solving scientifically meaningful challenges. Combined with the barriers to social learning discussed in Section 4.4, this results in significant difficulties during intermediate onboarding.

> *[The tutorials] are pretty [[pause]] light. They don't... go into any great detail. They pretty much show you what the basic controls do, and then throw you in the deep end.* (P13, Eyewire, Intermediate)

Earlier in conversation, P13 had explained that "Most of the skills that you actually use... the harder skills are not even attempted to be taught." Instead, he says, knowledge of these skills is gained through trial-and-error. P13's phrasing "then [they] throw you in the deep end" is also echoed by Eterna players, who note that there are no tutorials for the scientific challenges of the game. "The initial tutorial to learn basic skills to get access to the labs is quite good," says P16 (Eterna, Intermediate), "but after that, once you're in the labs there are no more tutorials."

On top of leaving out important concepts, the tutorials sometimes leave in extraneous concepts. P1 (Foldit, Intermediate) notes that Foldit's tutorial "...misses the mark in a lot of ways, I think. It teaches a lot of different tools that aren't really used in the normal metagame. And then the things that you do need to know, you more or less have to figure out from other players." Again, across these statements, we see the thread of social and exploratory learning as a fallback when the games fail to provide adequate instruction. If we look for instructional principles which might explain these frustrations, we see that Cognitive Load Theory — a commonly used theory in games research (e.g., [84, 95]) — identifies the extraneous concepts (tools not used in normal circumstances) left in tutorials as added cognitive load which increases mental effort and reduces learning efficiency [174].

Thus, ECCSG onboarding suffers from four types of missing instruction: a high entry skill barrier, a lack of sufficient feedback, a failure to explain the bigger picture, and a failure to teach all necessary concepts for intermediate to expert play. Although these problems are largely present for only the onboarding, the failure to teach intermediate and expert concepts remains an issue well into expert play, and the lack of sufficient feedback is a constant barrier throughout a player's journey to expertise. This is why the barrier of Missing Instruction has been placed on the on-ramp to the cycle of expertise in Figure 2: it is both an onboarding issue and a persistent barrier throughout the player's journey.

These failings are explainable by common instructional design principles [154, 174, 189]. As will be summarized in Table 3, ECCSG development teams can mitigate this barrier by collaborating with professional instructional designers, professional game designers, and expert players to provide effective and enjoyable tutorials that include in-depth feedback systems and a focus on the macro tasks, core gameplay loop, and contribution framework.

4.3 Missing Polish (The Game Barriers)

When it comes to promoting expertise, the game itself plays a key role as the central media artifact that players interact with. At the superficial level, players interact with the user interface (UI) and input control scheme. Beyond this gulf of execution is the gulf of evaluation [132], in this case the game design and gamification design of the task. Mediating this interaction on all levels is the technology, i.e., the game as software. Because expertise relies on exploratory learning, these levels of interaction are the interface between the player and their experiences in experimenting with the game. Alone, none of these levels are as obstructive as the instructional barrier; yet, each level of interaction is a frictive surface that slows, frustrates, and hinders learning and engagement.

The primary problems with the UI in current ECCSGs are a lack of discoverability and intuitive control. When combined with the instructional problems described above, this leads to an overwhelmingly difficult entry experience, as the tools one needs to play are hidden or difficult to navigate. And since viewing the problem is a critical first step to solving it [125], UI issues create downstream effects on solving the tasks at hand.

> *It is so hard to play Foldit if you don't know how to kind of manipulate what's in front of you. And if you lose the patience to do so, then that's hard.* (P1, Foldit, Intermediate)

Even compared to other molecular visualization software, Foldit's interface is described as "maddening," requiring "a lot of trial-and-error and frustration" (P4, Foldit, Expert) to get comfortable with tasks that P4 already knew how to do in other software. Another player described it as "fighting the UI a lot" (P12, Foldit, Intermediate), speaking directly to this wide gulf of execution. Even in Eyewire, the most difficult task is manipulating the camera and correlating between the 2D and 3D views of the game (P13, Eyewire, Intermediate).

Beyond the UI, there were many problems identified with the games' designs and mechanics, to the point where some participants questioned whether they were playing a game at all or simply scientific software made to seem exciting. The issues that participants raised were clear violations of what are normally considered heuristics of good game design: non-intuitive gameplay, unclear goals and scoring, and poor tutorial and level design [45, 46]. For example, P8 was confused by the core gameplay loop, lacking an understanding of the basic premise of how one is supposed to interact with the game:

> *It doesn't tell you that that's how it should be done. So I'm not sure that's how I'm supposed to do it.* (P8, Foldit, Novice)

To recall again the work of Iacovides et al., this breakdown of macro-level understanding inhibits involvement by not meeting the expectations of gameplay [86, 87]. In fact, the players have very few expectations. Macro-level expectations are informed by prior experience, other players, and the wider community [87]. Yet, new players often have no prior experiences with the niche of CSGs, and — as detailed below in Section 4.4 — there exist barriers to social onboarding, which includes expectation-setting. In this way, players have little precedent and preparation for what to expect from the game, and this creates friction when the game itself adds no further explanation.

However, a more common friction was participants describing a lack of reliability with the gameplay experience. For Foldit, this took the form of "finicky" tutorial levels:

> *It was like, I moved a sidechain and I wiggled it and I got the puzzle. I have no idea how. And you try the exact same thing. It didn't work the next time. You have no idea how it happened.* (P12, Foldit, Intermediate)

For Foldit players, whether they win a level or not with a given strategy seems up to chance; the game gives no feedback on how effective their strategy is or how they should improve, creating breakdowns of both action and understanding without opportunities for breakthroughs that might engage the player [87]. For Eyewire, this lack of reliability takes the form of skewed scoring in the gamification system. P13 describes how the AI agent which assigns tasks can make mistakes that penalize the player:

> *When I play Eyewire, mistakes made by other players and the game's level generator sometimes negatively impact my score. That is pretty discouraging. So I think the penalty and the scoring system could use quite a bit of improvement. [The participant later clarified that the game also severely and disproportionately punishes the player for "their own silly mistakes."]* (P13, Eyewire, Intermediate)

So not only do players struggle to interact with the game because of unintuitive controls, undiscoverable interfaces, and unclear gameplay rules, but when they are able to perform an action, the results are often unpredictable. This violates standard usability heuristics, such as Nielsen's principles [131] and the System Usability Scale [10, 24].

These issues are worsened by several technical difficulties that exist with these games. Such issues can add frustration and slow progress, which overall makes the experience more challenging to engage with. P3 (Foldit, Expert), for example, comments on how they sometimes wait for hours for the game to process: "You know, when somebody says, oh, I just did this and it came out like that and then I try it and, you know, four hours later and I'm still not getting a result. It's very frustrating. And I have a good machine." P5 (Foldit, Novice) expands on this, noting the ways in which frustration with technology interacts with the previously described gameplay confusions: "And if you don't know what you're doing and you poke at something for half an hour and your computer's running really slow, you really haven't made very much progress."

These two feelings: confusion and frustration, multiply against each other as the technical barriers of the game interact with the design barriers. Compare this to Paavilainen's modern definition of playability as functionality, usability, and gameplay [135]. Our findings map directly to Paavilainen's model as we have divided the Missing Polish into usability (UI), gameplay, and technology (functionality).

The exploratory learning phase of gaining expertise involves interacting with the game artifact. Yet, interaction involves both the gulf of execution and the gulf of evaluation through the UI and the gameplay, both levels mediated by the technology of the software itself. Frictions with the UI, the gameplay, and the technology can each hinder exploratory learning. These frictions lead to breakdowns in action, understanding, and eventually involvement [87].

Each of these frictions can be addressed in turn: ECCSG developers can collaborate with professional UI/UX designers to create clearer user interfaces; professional software developers can help optimize performance and reduce bugs; and professional game designers can help develop more intuitive gameplay using industry principles of tutorial design, level design, and gamification design.

4.4 Missing Communication (The Sociocultural Barriers)

Lastly, given the social nature of learning for ECCSGs, expertise depends heavily on strong, open communication. However, we found ECCSG communities largely lacking this communication due to factors such as a lack of adequate community content, gatekeeping, jargon, silence from the developers and scientists, and competitive restraints. These communication barriers prevent social learning, the second half of the explore-discuss cycle of learning. We examine each of these sociocultural issues in turn, separating them by player-player communications and player-developer communications.

First, there is not enough high-quality community content to scaffold learning. Other games, specifically popular commercial games, have in-depth wikis and dedicated content creators, such as YouTubers and Twitch streamers. Yet, this community content does not exist to the same extent for these CSGs, and furthermore there are gatekeepers and other barriers to enabling players to become content creators and address this inadequacy. Earlier, we described Minecraft: Education Edition as having more structured onboarding, but the commercial version of the game is still taught through a similar manner to ECCSGs (exploration and social learning).

> *Minecraft is a good example of a game where you basically learn the game from the wiki or you watch a YouTuber play it, you know, and you know, with Foldit, you don't really have that. You don't really have a lot of video content creators for the game.* (P1, Foldit, Intermediate)

With the amount of community content that exists for games like Minecraft, new players are easily assimilated into the affinity space of the game through a large number of "portals" (streamers, YouTubers, wiki guides, etc.) [67]. But, as P1 notes, ECCSGs have nearly no content creators. Furthermore, not only is the quantity lacking for ECCSGs, but the quality of the content itself is often poor due to a combination of low-quality recording hardware and editing software, inexperienced content creators, and complex game mechanics being discussed.

> *I'm done trying to find videos... I tried to watch something on YouTube. I tried to find some videos and I [found] a few tutorials. I watched them and they [were] in very, very ugly quality. And a few of them [were] too complicated for me, who just started ... playing.* (P7, Foldit, Intermediate)

In essence, ECCSGs are following a model of cognitive apprenticeship [36], wherein the professional vision is modeled by content creators and observed by new members to the affinity space. This same model has recently become popular on Twitch for domains such as coding [58] and eSports [70]. Similarly, wikis also provide a portal into the affinity space and allow learners to co-construct knowledge as another form of cognitive apprenticeship [200]. Yet, although ECCSGs are following this practice, they do not have the same level of organized, published information or archives of content that more successful domains have. P13 notes this when comparing Eyewire to the board game Go:

> *So when I'm learning both Go and Eyewire, I assemble heuristics and create my decision tree based on those rules... For Go, is, is an ancient game and there are quite a few books and, rules of thumb, heuristic type things that have been developed by a lot of people... For Eyewire, the heuristics aren't really listed anywhere.* (P13, Eyewire, Intermediate)

On the surface, it seems that both the low quality and quantity of community content could be attributed simply to a smaller community size. However, upon further investigation, this was not the only factor — ECCSGs have specific barriers further preventing content creation. When players were asked why they do not contribute to creating content themselves, several typical responses were given, such as a lack of time (not being able to fit it into their schedules). Yet, two other responses were frequently given which appear to be unique to expertise-centric games: a sense of inadequacy and a fear of how the content would be received.

> *I'm not really a guy that tries to go out and make videos real quick and edit wikis until I know that I'm very knowledgeable on what I'm talking about... Right now, I'm not comfortable with like showing how I'm playing... And I would not be comfortable trying to edit the wiki. These guys [other players] know way too much.* (P11, Foldit, Intermediate[15])

[15]Recall that intermediate players typically have *years* of experience. The fact that they still do not feel able to create content of any kind is striking. This opinion was expressed by several intermediate players.

Previous literature has also identified learner confidence as a barrier to making contributions to community content [117]. Furthermore, a study of Wikipedia found several related factors important in making contributions, including (among others) a sense of belonging, altruism, attitude, subjective norms, and knowledge self-efficacy [32]. It seems that in the case of ECCSGs, knowledge self-efficacy (causing sense of inadequacy) and sense of belonging (causing fear of reception) are two potentially limiting factors inhibiting the intent to contribute. This is further evidenced by P13 (Eyewire, Intermediate), who said he didn't make content because he was "a little worried about stepping on toes," a sentiment echoed by another participant who described "Getting to the point where I knew enough of the players" (P16, Eterna, Intermediate) as a prerequisite to creating community content. To these players, having a strong social network and the social status associated with it — i.e., a sense of belonging — appears to be a requirement for creating content (as well as for extended participation, cf. [9]).

In addition to these two factors, knowledge self-efficacy and sense of belonging, players can also be pressured by explicit gatekeeping from developers if their contributions are not perceived as accepted or acceptable:

> *I've thought about reorganizing the Eterna wiki. But there's a lot on there and it's hard to find, not very well organized... It's a ton of work, and I have a feeling, from what I've seen, it would be dismissed... Probably wouldn't be accepted... It probably would be wasted time... Probably no one else would agree on it and it would never go anywhere... I've seen a lot of other players spend a lot of time creating content and tutorials and organizing things, and it just gets ignored. [Interviewer: Does it get ignored by the players or the developers or both?] The developers.* (P16, Eterna, Intermediate)

We also observed that some of the participants who noted this gatekeeping were women. A recent study on Wikipedia contributions found a gender bias due to a "vicious circle" of negative reputation, anonymity, fear, alienation, and rejection [118]. The authors note that several sociocultural barriers occur both pre- and post-contribution. A similar set of issues may be occurring in ECCSG community content contributions as gatekeepers prevent women from contributing knowledge in these spaces. Recognizing player contributions is therefore critical for supporting community content, especially because it speaks directly to the motivations of players who want to be recognized for their contributions in the CSG [43, 50, 88, 91].

Our findings regarding social learning relate to the Creativity component of the MLC model [91]. As Jennett et al. write, online citizen science learning is "informal, unstructured and social," and it follows a virtuous circle: "a volunteer improves her knowledge and skills by doing the task, sharing this in a community of peers helps to increase her self-confidence, also increasing her ability to perform the task and her desire to share ... the community helps her to become more competent, which will finally enable her to help newcomers in the community, therefore becoming conscious of her learning and more self-confident in both performing the task and assuming new roles in the community" [91, p. 15]. Yet with ECCSGs, we found that a lack of knowledge self-efficacy and sense of belonging inhibit players from sharing back to the community, thus breaking this cycle and preventing community-based learning. In fact, it's possible (though left for future work) that the only causal factor here is knowledge self-efficacy — that a low sense of belonging is a symptom rather than cause of this barrier. Indeed, by definition, most of the differences between ECCSGs and other citizen science projects is the emphasis of expertise, which is what appears to be triggering the low knowledge self-efficacy and could hardly explain the low sense of belonging without other mediating factors.

Moreover, although it is clear that social learning is a critical factor, participants expressed dissatisfaction with the current channels of communication. This includes player-player communication, such as chat channels being too quiet (P4, Foldit, Expert). However, more often participants discussed issues with the communication between the players and the science/development team. For example, scientific jargon is a strongly demotivating factor for novice players:

> *I try to [follow Foldit news]. But then to a certain point, you know, [the news post] starts to talk about things which I just don't understand. And then, you know, it just kind of... at that point I don't pay much attention.* (P6, Foldit, Novice)

Novice players often don't have the prior knowledge to understand the jargon being used to describe scientific progress. Moreover, this struggle is not restricted to novices — even players with years of experience feel doubt about engaging with news updates from the scientists.

> *[On the subject of when communication breaks down] The short answer on this is: jargon. They're using scientific jargon that we don't understand... Players have to ask a lot of questions, because it's unclear to us. We have to ask a lot of questions. And I'm the, I end up being the one who asks a lot of questions. And I don't know if that's because it's just not occurring to other people to ask these questions or they're embarrassed and don't want to look stupid, but. I, and even I at some point hesitate to ask any more questions because, like, I'm worried, it's making me look uninformed... to be asking too many questions.* (P16, Eterna, Intermediate)

Studies on scientific communication have found that jargon can reduce perceived and actual understanding and can even affect scientific interest, information-seeking behavior, and potentially self-identification with the scientific community [26, 168]. Because of their deeply-ingrained expertise (and lack of public communication training [136]), scientists may struggle to avoid jargon while communicating [152] (although some evidence suggests that scientist communication can be a viable alternative when professional communication is not available [12]). However, this is assuming that the scientists communicate at all. In some cases, players are simply disappointed with the frequency and transparency of scientific updates:

> *I also am concerned that the science behind the... We never, we don't see hardly any results of this development... They occasionally will come out once or twice a year and say we mapped this neuron and show a picture or a collection of neurons. But nobody's really saying what actually they are learning from it or what they are trying to learn from it.* (P13, Eyewire, Intermediate)

A lack of communication, especially regarding the outcomes of player contributions, can be seriously demotivating for players. Yet, even before players attempt to engage with blog posts and other updates from the science team (where present), confusions already arise from the game itself. Players have outstanding confusions about the citizen science components of ECCSGs and how their play affects scientific research. The game-science research loop — the fundamental core of ECCSGs — is not described adequately to them:

> *I'm very iffy on what it means to create a solution in Foldit and then somehow that goes into the lab... I still don't really know much about how that happens.* (P11, Foldit, Intermediate)

Given that the premise of CSGs is that anyone can contribute to scientific progress, one would expect that the game itself would adequately explain everything the player needs to know about their contributions; the player shouldn't need to seek out other information sources on the contribution model, yet players are going years without understanding the game they are contributing to. Similarly, there is little to no feedback to the players about their performance, so they feel confused about whether they are making meaningful contributions as they play. "It's difficult to tell [that] what you're doing in the game matters at all..." says P8 (Foldit, Novice). Compare this to the earlier finding that making meaningful scientific contributions is a core motivating factor for sticking with an ECCSG. If players cannot understand how their contributions are meaningful, then they cannot value the game for making contributions, and so they are much more likely to abandon the game.

These results agree with the findings of Díaz et al. [50]. For example, one of their participants said their experience was "Fun but frustrating, it would be nice to have a better understanding of how the data helps real life research. Enjoyable game, but I lost interest due to the perceived disconnect from the science behind it."

Scientific communication is difficult, not just in CSGs but in citizen science more broadly [136, 157] (and, indeed, in all public communications). For in-depth solutions, we refer to Rüfenacht et al. [157] who recommend, among other steps, appointing a communications expert to the core team and developing a communication and dissemination strategy.

Although we have divided this analysis between player-player and player-developer communications, all communications are ultimately shaped by the design and development of the project. The player-player communication barriers — most notably low knowledge self-efficacy and low sense of belonging — are entangled with the instructional barriers and influenced by the project's onboarding design. Thus, despite developers not being directly involved in interplayer communication, they still have the power to moderate, mediate, and manipulate it.

4.4.3 Tension between open science and secret competition. Notably, within Foldit only, participants described a tension in the game that stems from the dynamic of groups (teams) which are both private and competing.

> *So people are still reluctant to share certain things outside of the group setting. So, you know, where, in group [chat], I might be talking about some overall strategy about low energy or clash importance, in veteran [a more public chat channel] I wouldn't talk about that at all. And, you know, I've had people in veteran say, well, how did you do that? And my first knee-jerk reaction is to tell them. And then my second reaction is, well, wait a minute. You know, that's something my group would want to know, but I'm not sure I want to tell you. And, you know, it's science so we all benefit. So why don't we all do it? So there's that tension between the two.* (P3, Foldit, Expert)

From a novice perspective, and indeed from the perspective of a collaboration toward open science, the idea of hiding knowledge for personal gain is paradoxical to the ECCSG's mission.

> *I'm a new player. I would benefit greatly from new solutions, but I don't have access because I might compete with this player and my group might benefit from theirs... There is some level of weird sort of friction that's like, I can't receive help from you because you're on the other group... There's such a level of secrecy placed on sharing solutions that it's completely unwarranted.* (P8, Foldit, Novice)

This tension was previously identified by Ponti et al. [140], so our purpose here is only to confirm their work, not to unveil a new phenomenon. Yet, we highlight it here because it may speak to a larger tension: the tension between *game* and *science* in citizen science games. Of all dilemmas (in the Triadic Game Design sense of the word [77]), the tensions between game and science seem to be most often in conflict for ECCSGs. We speculate this is due to the lack of specialized persons with both scientific and game design expertise, as suggested by Prestopnik and Crowston [143]. It is unlikely that these two domains are inherently incompatible; rather, CSG development teams have historically lacked sufficient expertise in one or the other. In any case, the takeaway message from this is to approach competition mechanics with caution, since competition is the driving force creating secrecy in Foldit.

In summary, we see several major barriers to social learning in ECCSGs: small communities, low knowledge self-efficacy, low sense of belonging, community content gatekeeping, inaccessible scientific communication, infrequent scientific communication, and the tensions of competition. The issue of small communities is confounded with other factors that make ECCSGs a niche community, while the issues of low knowledge self-efficacy, low sense of belonging, and community content gatekeeping (i.e., developer dismissal of paratext contributions) appear to be unique to ECCSGs and a novel finding of this work. These barriers may be lowered by making community engagement more accessible, such as by providing technical and social assistance for creating content and encouraging forms of engagement that don't require expert knowledge. The next two barriers, inaccessible and infrequent scientific communication, are known problems in the broader fields of citizen science and general science dissemination, and solvable using recommendations from prior literature, such as regular communication schedules [136, 152, 157, 168]. Lastly, the tensions between group competition and open science were first identified by Ponti et al. [140]. We expand on their finding by placing it in the context of a broader tension between the *game* and *science* of citizen science games, as also seen in Section 4.1.1 on the various ways science knowledge interplays with game expertise.

5 DISCUSSION

Through interviews with ECCSG players of varying expertise, we generated four themes to describe the path to expertise and barriers in this path. The first barrier players encounter is Missing Instruction. Then, as players begin a cycle of exploration and social learning toward expertise, they encounter the barriers of Missing Polish and Missing Communication which inhibit their exploratory and social learning respectively.

The golden path to expertise is social and exploratory. One's initial engagement may be driven by an interest in contributing to science or for personal reasons (such as entertainment or personal learning), but continued engagement depends on both of these motivations being present simultaneously. Once expertise is reached, one gains a "professional vision," or an understanding of seeing, discussing, and thinking about the game that is shared with other experts [72, 141]. This reflects the case study of Apolyton University — a player-made online community of *Civilization* players [172]. This community's online discussions of incredibly nuanced topics and their protocols for novice player onboarding, as Squire describes, is an exceptional example of knowledge production and organization, design thinking, and social learning with cognitive apprenticeship. Squire's case study demonstrates that game communities are capable of managing extreme expertise. Here too, we see an exploratory, social approach to gaining expertise and a shared understanding of that expertise within the community.

As such, for CSG developers to teach in the ways that players learn, we recommend leaning into the social and exploratory aspects of game-based learning. This can include, for example, social features to better enable inter-player communication, in-game wikis, and modes of play that encourage and support exploration. Moreover, we encourage CSG developers to appoint professional community managers to maintain the social spaces of their community, as suggested by other citizen science scholars [108, 157, 191].

The first set of barriers on this path is instructional, introduced by a lack of clear goals and strategies. First and foremost, players in this study and in prior literature (e.g., [50, 141]) widely agree that ECCSGs have incredibly steep learning curves on initial entry. Paradoxically, the tutorials are simultaneously too simple and the gameplay too difficult, namely because the tutorials focus on micro tasks and basic control schemes without introducing more advanced, nuanced concepts that are required for standard expert play.

This design paradigm creates what we will call the "**giant's staircase**," where difficulty begins flat and trivial and suddenly spikes to insurmountable heights. With complex games like Foldit, there may be several such levels of giant's steps, meaning that even if you can overcome one giant step, there may be more remaining between intermediate and expert play, alternating between trivial and impossible.

The lack of teaching all critical concepts is especially noteworthy in that these games fail to teach the big picture of what the game is even about and how playing is contributing to science. By focusing on the micro tasks, it is not made clear to players what the macro tasks are and how these skills and tools connect to a broader impact. Lastly, there is a distinct lack of feedback given to players to help them improve their play. This is in part due to the qualitative and unknown nature of scientific contribution, yet there exist current and potential social and ludic dynamics which can overcome this challenge and provide feedback, as noted by player suggestions during the interviews.

Overall, our findings on the instructional barriers of ECCSGs agree with prior literature on the low efficacy of CSG tutorials and need for better explanations on the scientific contribution models [50, 115, 170]. We therefore recommend appointing professional instructional designers who can create effective training materials and professional game designers who can make such materials enjoyable. Moreover, given how important the big picture, core gameplay loop, and scientific contribution model are to understanding and contributing, it is critical to teach these early and refer to them often, such as via the "whole-task" approach of 4C/ID [189]. Lastly, for teaching advanced gameplay topics, collaboration with expert players is important to ensure that expert strategies are taught and taught well.

The second set of barriers on this path is game-based, introduced by a lack of polish on the game software itself. Confusions and frustrations are caused by a disorganized user interface, slow or aging technology, and unintuitive gameplay. Further, the gamification elements are sometimes in conflict with the scientific goals, leading players to behave ineffectively. The lack of clarity in goals may also unintentionally encourage players to play in a way that is not engaging for them, further defeating the purpose of the CSG.

As shown in prior literature, citizen science technologies often suffer from poorly designed user interfaces [170] and technical issues which can reduce participation and data collection [63, 165, 184]. Similarly, historical attempts at gamifying citizen science in ways that aren't aligned with scientific goals (e.g., competition) can lead to disinterest and discontinued participation [57]. Citizen science games are "system assemblages" of many technologies, which requires careful attention toward integrating these systems in order to support participation and the scientific goals of the project [146]. We therefore suggest employing professional UI/UX designers, software developers, and game designers to provide the necessary polish required for an engaging and operational CSG.

The third set of barriers on this path is sociocultural, introduced by a lack of open communication. Discourse is limited by incompatible sets of jargon between players and scientists, and restricted by low knowledge self-efficacy, low sense of belonging, and developer gatekeeping. Fear of gatekeeping and a sense of inadequate expertise and belonging prevents the creation of community content, further limiting knowledge sharing. Moreover, players expressed dissatisfaction with the amount of feedback they receive from scientists and developers. Within Foldit specifically, there is also a tension between the secretive, competitive gameplay and the overt goal of open science contributions, as previously noted by Ponti et al. [140].

These findings agree with recently discovered mechanisms of community content contributions [32] and scientific jargon [26, 168]. Therefore, we recommend CSG developers provide technical and social assistance for encouraging community content while discouraging and preventing gatekeeping. Working with community managers and science journalists can help the team create and execute a strong communication and dissemination strategy and become more accessible and transparent in their scientific communications, as detailed in recent citizen science publications [136, 157].

We also note the entanglement of these three sets of barriers. Although each barrier is a distinct cause of problems from a separate design space, together they overlap in symptoms and create interaction effects. For example, consider Foldit's "finicky" tutorials. On the surface, this issue is caused by inconsistent game mechanics or otherwise poor game design. Yet, the issue would not be so frustrating if the game also provided clear and thorough feedback or access to high-quality community-made guides to help players reach the goal. Meanwhile, players are simultaneously struggling with a complex UI, slow technology, a steep learning curve, etc. In this way, removing only one of these barriers may not even resolve the issues, or may resolve one but surface another.

This work supports previous literature on player experiences in CSGs. As found by Eveleigh et al. [56], we observed that intrinsic motivation leads to deep engagement, and that initial participation may be increased by acknowledging contribution efforts and enabling the players to fit the game around their existing schedules. Like Díaz et al. [50], we found that players thought the tutorials were too simple and the game too difficult, and that players want more explanation of the science and the overall goals of the project. Finally, echoing Skarlatidou et al. [170] and Spiers et al. [171], players expressed desires for better tutorials and larger, more diverse communities.

Prior research shows that game communities use games to learn experientially via active and discovery learning, forming affinity groups, cycles of expertise, well-ordered problems, and simplifying conditions [64, 66, 68, 154, 172]. In ECCSGs, we respectively saw exploratory learning, community knowledge building, cycles of exploration and social learning, and tutorials which attempt to simplify and order the problem space (despite their failings described in Section 4.2).

Similarly, our findings are consistent with Jennett et al.'s MLC model and their barriers to engagement, which included difficult or boring tasks and lack of time [91]. We found lack of time cited as a reason for not contributing community content and difficult tasks to be the primary symptom of instructional failings. These results are also in agreement with Aristeidou et al.'s factors of participation, namely lack of time, website usability, fear (of engagement), quality of contributions, and sense of belonging [9]. Specifically, we found that low knowledge self-efficacy was a unique factor to ECCSGs and likely drove fear of engagement and sense of belonging.

The rest of this section places this work in broader contexts and discusses implications. First, in the broader context of CSGs, to what extent does expertise matter at all? As suggested by Eveleigh et al. [56], perhaps some participants don't want to be experts, only dabblers. However, dabbling appears to be incongruous with ECCSGs. Unlike data-centric CSGs where contributions are proportional to effort, ECCSGs have an exponential curve with respect to effort versus output: a great deal of investment at the beginning of one's play will amount to little usable output, but after initial investments to learn the domain, even a small amount of effort will produce valuable contributions. In this way, as ECCSGs are currently designed, the effort of dabblers (excluding those with pre-existing expertise) is better spent elsewhere, such as on data-centric projects.

Next, there is the "elephant in the room" issue noticeably brought up by our findings — if the solution to many of the barriers to expertise is to hire professionals with varying skill sets, how ought CSG teams accomplish this with the current state of funding? Typically, CSGs are funded much like educational technologies via research labs and government grants [104]. To a lesser extent, they can also be funded by private donations; and although some citizen science projects are funded by entrepreneurial sources such as participant fees and merchandise sales, no CSGs (to our knowledge) employ that participant-funded model at this time [197]. CSGs therefore have no sustainable financial model, especially given that research grants rarely cover long-term project maintenance [104]. Klopfer et al. [104] posit that educational technologies might look to entrepreneurial incubators and startups to help turn their products revenue-positive in order to become sustainable, perhaps even employing a hybrid model where technologies are prototyped via research grants and polished via entrepreneurial partners. However, transferring this model to CSGs would raise new ethical questions if, for example, the ability to contribute to scientific knowledge becomes locked behind paywalls. In short, there is no easy solution to broadening CSG teams to include a wider array of expertise given the current financial infrastructure. Instead, we suggest CSG teams begin investigating these alternative funding sources (exploring their ethical implications beforehand) and secondly reach out to experts who may be willing to offer some *pro bono* assistance.

Our study answers an important research gap: why is ECCSG onboarding currently insufficient, and in what ways? Specifically, this work provides two major contributions to this question. First, we present a model of how expertise is acquired in ECCSGs and the barriers along that path. This extends previous work on CSGs with respect to understanding expertise [97], player experiences

	Findings and Recommendations	Expected Generality	Contribution
Path to Expertise	**Learning is exploratory and social**	Broad	Validates [91]
	Learning is a *cycle*: exploratory *then* social Improve social learning by adding or improving social features for connecting players both in-game and through other channels, such as wikis, forums, Discord servers, and community content. Collaborate with professional community managers. Improve exploratory learning by adding ludic features which encourage exploration and intelligent trial-and-error.	ECCSGs	Novel, cf. cycles of expertise [66] and GIIL [89]
	Motivation requires both meaningful contribution and self-gain Consider how the game feeds player motivations for contributions to science, entertainment, and personal learning; provide features to address all of these motivators.	CSGs	Extends [43, 91, 177]
	ECCSG players develop a "professional vision"	ECCSGs	Extends [141]
Missing Instruction	**Entry skill barrier** Collaborate with professional instructional designers and game designers to provide effective and enjoyable task progressions.	ECCSGs	Novel
	Lack of feedback Provide social features for in-depth peer-to-peer feedback. Provide dynamic automated feedback within the game. Provide frequent communication from the scientists regarding how contributions are being used and the results of scientific analysis.	ECCSGs	Novel, cf. [55]
	Part-task approach Teach the big picture, macro tasks, core gameplay loop, and contribution framework early.	ECCSGs	Novel, cf. [55, 189]
	Ends instruction early Collaborate with expert players to understand and teach the advanced techniques required for intermediate to expert play.	ECCSGs	Novel
Missing Polish	**Unintuitive UI/UX** Collaborate with professional UI/UX designers to develop clear, organized user interfaces.	CSGs	Extends [50, 134]
	Technical issues Collaborate with professional software developers to optimize performance for typical usage, especially novice play.	CSGs	Extends [50, 134]
	Unclear gameplay Collaborate with professional game designers to develop clear and intuitive gameplay using industry principles of tutorial and level design.	CSGs	Extends [50, 134]
Missing Communication	**Low knowledge self-efficacy** Make contributing community content more accessible for all players by providing technical and social assistance.	ECCSGs	Novel, cf. [76]
	Low sense of belonging Detach perceived game skill from perceived ability to contribute by encouraging other forms of community content contribution, such as fan art and social events.	ECCSGs	Novel, cf. [13, 14]
	Community content gatekeeping Explicitly address, discourage, and prevent gatekeeping.	ECCSGs	Novel, cf. [118]
	Insufficient scientific communication Provide more details on the scientific topic and acknowledgements/praise of player contributions with details of how their efforts translate to scientific advance. Invite open communication. Collaborate with communicators and science journalists to provide clear, public-facing translations of scientific jargon.	Broad	Validates [136, 152, 157, 168]
	Tensions of competition Design for collaborative rather than competitive gameplay. Look for and eliminate game dynamics which encourage secrecy.	Foldit	Validates [140]

Table 3: A summary of findings and recommendations addressing the issues identified in the reflexive thematic analysis.

[50], and skill acquisition [124] and adds a specific framework for how skill-based expertise is acquired and the ways in which its acquisition is hindered. Second, we identify three barriers to expertise and unpack detailed mechanisms of how they interfere with learning and engagement. With respect to instruction, the mechanisms are: high skill requirements on entry, lack of feedback, lack of a big picture explanation, and lack of intermediate-to-expert instruction. With respect to the game artifact, the mechanisms are: unintuitive and cluttered user interfaces, software issues, and unclear gameplay. With respect to the interpersonal, the mechanisms are: low knowledge self-efficacy, low sense of belonging, content

gatekeeping, inaccessible and infrequent scientific communication, and game-science tensions.

Notice also that — when taken abstractly — only the sociocultural barriers are specific to the unique science-game model of ECCSGs. The game-based barriers (poor UI, software, and gameplay) could be found in any game, and the instructional barriers (poor instructional design) could be found in learning any topic for which learning materials do not exist in abundance. Therefore, we expect this work to be useful as a guide to product refinement for other fields of game-based learning, such as the iterative development of educational technologies and serious games.

We provide a summary of our findings in Table 3, noting where our contributions are novel or extend/validate prior literature. Importantly, because this work is strongly interdisciplinary, many of our findings can be linked to prior theory in learning sciences. While we aimed to note as many connections as possible, what we list as novel contributions is meant to highlight original observations specifically in ECCSGs.

This study is not without limitations. The first and foremost limitation is a small and mostly homogeneous sample. More evidence is needed to confirm this model, especially in Eyewire and Eterna. Moreover, despite its potential, there is little evidence to support generality outside of ECCSGs, which are quite a niche field. Nevertheless, this exploratory work provides direction for future research in dismantling the barriers and accessibility issues which prevent citizens from contributing human computation and creativity toward scientific advancement. As the 21st century continues to show a need for effective mass cooperation and interpersonal efforts in a variety of ways, this work contributes toward our understanding of interdisciplinary and complementary expertise in the example of game players gaining and contributing expertise to scientific research.

Though this work is meant for ECCSGs, other game-based learning projects may benefit from understanding the barriers to player learning. Projects which meet any of the expertise-centric criteria — from gamified language learning to game-based algorithm discovery — can learn from the ECCSG model how to better empower their users' learning and the ways in which learning and contributing are suppressed.

What are the takeaways and implications for the future of ECCSGs? Considering the arguments of Keep, it is critical to focus on improvements to knowledge sharing, knowledge organization, and discourse translation between players and scientists [97]. Moreover, as discussed in subsection 2.4, this work suggests possible ideas in the design space of ECCSGs. Any projects needing the affordances of ECCSG criteria — addressing a system-driven, self-contained, complex problem space with many problems to solve — may consider making their project into an ECCSG.

For future work, the next step for improving ECCSGs is to remove these barriers via design-centered research. A table of recommendations for topics of improvement based on these themes is provided for CSG developers in Table 3.

6 CONCLUSION

The expertise-centric CSG can be a powerful framework for crowdsourcing scientific advancement, yet in practice they are incredibly difficult to design well. For the ECCSG to be effective, it must train its players in how to become experts. In this study, we interviewed ECCSG players of Foldit, Eterna, and Eyewire, then applied reflexive thematic analysis to generate themes of their experiences. The analysis produced a model of expertise in ECCSGs and barriers therein. The path to expertise was found to be a cycle of exploratory learning — yet hindered by a lack of game polish — and social learning, hindered by a lack of communication. Entrance to, and repetition of, this cycle is barred by poor instructional design, nicknamed the "giant's staircase." This work validates and extends several previous studies on player experiences in CSGs. Based on this work, we call into question the current financial and participatory models of CSGs and make recommendations for CSG developers, including collaborating with professionals of required skill sets, providing social features and feedback systems, and improving scientific communication.

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REFERENCES

[1] 2021. iNaturalist. Retrieved from https://inaturalist.org/ on December 2, 2021.
[2] 2021. Player-Created Guides. Retrieved from http://eternawiki.org/wiki/index.php5/Player-Created_Guides on November 29, 2021.
[3] 2021. Zooniverse. Retrieved from https://www.zooniverse.org/ on December 2, 2021.
[4] Rebecca Rashid Achterman. 2019. Minds at play: Using an online protein folding game, Foldit, to support student learning about protein folding, structure, and the scientific process. *Journal of microbiology & biology education* 20, 3 (2019), 100.
[5] Marc Malmdorf Andersen and Andreas Roepstorff. 2021. Play in Predictive Minds: A Cognitive Theory of Play. (2021).
[6] Aditya Anupam. 2021. Can Digital Games Teach Scientific Inquiry? A Case of How Affordances Can Become Constraints. *Proceedings of the ACM on Human-Computer Interaction* 5, CHI PLAY (2021), 1–21.
[7] Louise Archer, Emily Dawson, Jennifer DeWitt, Amy Seakins, and Billy Wong. 2015. "Science capital": A conceptual, methodological, and empirical argument for extending bourdieusian notions of capital beyond the arts. *Journal of Research in Science Teaching* 52, 7 (2015), 922–948.
[8] Maria Aristeidou, Eileen Scanlon, and Mike Sharples. 2015. Weather-it: evolution of an online community for citizen inquiry. In *Proceedings of the 15th International Conference on Knowledge Technologies and Data-driven Business*. 1–8.
[9] Maria Aristeidou, Eileen Scanlon, and Mike Sharples. 2017. Profiles of engagement in online communities of citizen science participation. *Computers in Human Behavior* 74 (2017), 246–256.
[10] Aaron Bangor, Philip T Kortum, and James T Miller. 2008. An empirical evaluation of the system usability scale. *Intl. Journal of Human–Computer Interaction* 24, 6 (2008), 574–594.
[11] David Bar-El and Kathryn E. Ringland. 2020. Crafting Game-Based Learning: An Analysis of Lessons for Minecraft Education Edition. In *International Conference on the Foundations of Digital Games*. 1–4.
[12] Yael Barel-Ben David, Erez S Garty, and Ayelet Baram-Tsabari. 2020. Can scientists fill the science journalism void? Online public engagement with science stories authored by scientists. *PloS one* 15, 1 (2020), e0222250.
[13] Roy F Baumeister and Mark R Leary. 1995. The need to belong: desire for interpersonal attachments as a fundamental human motivation. *Psychological bulletin* 117, 3 (1995), 497.
[14] Roy F Baumeister, Jean M Twenge, and Christopher K Nuss. 2002. Effects of social exclusion on cognitive processes: anticipated aloneness reduces intelligent thought. *Journal of personality and social psychology* 83, 4 (2002), 817.
[15] Elizabeth Bonsignore, Derek Hansen, Kari Kraus, and Marc Ruppel. 2013. Alternate reality games as platforms for practicing 21st-century literacies. (2013).
[16] Anne Bowser, Derek Hansen, Yurong He, Carol Boston, Matthew Reid, Logan Gunnell, and Jennifer Preece. 2013. Using Gamification to Inspire New Citizen Science Volunteers. In *Proceedings of the First International Conference on Gameful Design, Research, and Applications* (Toronto, Ontario, Canada) *(Gamification '13)*. Association for Computing Machinery, New York, NY, USA, 18–25.

https://doi.org/10.1145/2583008.2583011
[17] Anne Bowser, Derek Hansen, and Jennifer Preece. 2013. Gamifying citizen science: Lessons and future directions. In *Workshop on Designing Gamification: Creating Gameful and Playful Experiences*.
[18] Alan Boyle. 2020. A protein puzzle game called Foldit turns up 99 promising ways to confound coronavirus. https://www.geekwire.com/2020/protein-puzzle-game-called-foldit-turns-99-promising-ways-confound-coronavirus/
[19] Daren C Brabham. 2013. Crowdsourcing. Massachusetts Institute of Technology.
[20] Virginia Braun and Victoria Clarke. 2006. Using thematic analysis in psychology. *Qualitative research in psychology* 3, 2 (2006), 77–101.
[21] Virginia Braun and Victoria Clarke. 2019. Reflecting on reflexive thematic analysis. *Qualitative Research in Sport, Exercise and Health* 11, 4 (2019), 589–597.
[22] Virginia Braun and Victoria Clarke. 2019. To saturate or not to saturate? Questioning data saturation as a useful concept for thematic analysis and sample-size rationales. *Qualitative Research in Sport, Exercise and Health* (2019), 1–16.
[23] Virginia Braun and Victoria Clarke. 2021. Can I use TA? Should I use TA? Should I not use TA? Comparing reflexive thematic analysis and other pattern-based qualitative analytic approaches. *Counselling and Psychotherapy Research* 21, 1 (2021), 37–47.
[24] John Brooke et al. 1996. SUS-A quick and dirty usability scale. *Usability evaluation in industry* 189, 194 (1996), 4–7.
[25] Ann L Brown and Joseph C Campione. 1994. *Guided discovery in a community of learners.* The MIT Press.
[26] Olivia M Bullock, Daniel Colón Amill, Hillary C Shulman, and Graham N Dixon. 2019. Jargon as a barrier to effective science communication: Evidence from metacognition. *Public Understanding of Science* 28, 7 (2019), 845–853.
[27] Gordon Calleja. 2011. *In-game: From immersion to incorporation.* mit Press.
[28] Luigi Ceccaroni, Anne Bowser, and Peter Brenton. 2017. Civic education and citizen science: Definitions, categories, knowledge representation. In *Analyzing the role of citizen science in modern research.* IGI Global, 1–23.
[29] William G. Chase and Herbert A. Simon. 1973. Perception in chess. *Cognitive psychology* 4, 1 (1973), 55–81.
[30] Jenova Chen. 2007. Flow in games (and everything else). *Commun. ACM* 50, 4 (2007), 31–34.
[31] Michelene TH Chi, Paul J Feltovich, and Robert Glaser. 1981. Categorization and representation of physics problems by experts and novices. *Cognitive science* 5, 2 (1981), 121–152.
[32] Hichang Cho, MeiHui Chen, and Siyoung Chung. 2010. Testing an integrative theoretical model of knowledge-sharing behavior in the context of Wikipedia. *Journal of the American Society for Information Science and Technology* 61, 6 (2010), 1198–1212.
[33] Richard Clark. 2014. Cognitive task analysis for expert-based instruction in healthcare. In *Handbook of research on educational communications and technology.* Springer, 541–551.
[34] Richard E Clark, Kenneth Yates, Sean Early, and Kathrine Moulton. 2009. An analysis of the failure of electronic media and discovery-based learning: Evidence for the performance benefits of guided training methods. *Handbook of Improving Performance in the Workplace: Volumes 1-3* (2009), 263–297.
[35] Cassandra Coburn. 2014. Play to cure: Genes in space. *The Lancet Oncology* 15, 7 (2014), 688.
[36] Allan Collins. 1991. Cognitive apprenticeship and instructional technology. *Educational values and cognitive instruction: Implications for reform* 1991 (1991), 121–138.
[37] Mia Consalvo. 2017. When paratexts become texts: de-centering the game-as-text. *Critical Studies in Media Communication* 34, 2 (2017), 177–183.
[38] Seth Cooper. 2014. *A framework for scientific discovery through video games.* Morgan & Claypool.
[39] Seth Cooper, Firas Khatib, Ilya Makedon, Hao Lu, Janos Barbero, David Baker, James Fogarty, Zoran Popović, and Foldit Players. 2011. Analysis of social gameplay macros in the Foldit cookbook. In *Proceedings of the 6th International Conference on Foundations of Digital Games.* 9–14.
[40] Seth Cooper, Firas Khatib, Adrien Treuille, Janos Barbero, Jeehyung Lee, Michael Beenen, Andrew Leaver-Fay, David Baker, Zoran Popović, et al. 2010. Predicting protein structures with a multiplayer online game. *Nature* 466, 7307 (2010), 756.
[41] Seth Cooper, Adrien Treuille, Janos Barbero, Andrew Leaver-Fay, Kathleen Tuite, Firas Khatib, Alex Cho Snyder, Michael Beenen, David Salesin, David Baker, et al. 2010. The challenge of designing scientific discovery games. In *Proceedings of the Fifth international Conference on the Foundations of Digital Games.* 40–47.
[42] Justin Cranshaw and Aniket Kittur. 2011. The polymath project: lessons from a successful online collaboration in mathematics. In *Proceedings of the SIGCHI conference on human factors in computing systems.* 1865–1874.
[43] Vickie Curtis. 2015. Motivation to participate in an online citizen science game: A study of Foldit. *Science Communication* 37, 6 (2015), 723–746.
[44] Vickie Curtis. 2018. Who Takes Part in Online Citizen Science? In *Online Citizen Science and the Widening of Academia.* Springer, 45–68.
[45] Heather Desurvire, Martin Caplan, and Jozsef A Toth. 2004. Using heuristics to evaluate the playability of games. In *CHI'04 extended abstracts on Human factors in computing systems.* ACM, 1509–1512.
[46] Heather Desurvire and Charlotte Wiberg. 2009. Game usability heuristics (PLAY) for evaluating and designing better games: The next iteration. In *International Conference on Online Communities and Social Computing.* Springer, 557–566.
[47] Sebastian Deterding. 2013. *Modes of play: A frame analytic account of video game play.* Ph.D. Dissertation. Staats-und Universitätsbibliothek Hamburg Carl von Ossietzky.
[48] Sebastian Deterding. 2014. The ambiguity of games: Histories and discourses of a gameful world. *SP Walz, & S. Deterding, The Gameful World: Approaches, Issues, Applications* (2014), 23–64.
[49] Sebastian Deterding, Dan Dixon, Rilla Khaled, and Lennart Nacke. 2011. From game design elements to gamefulness: defining" gamification". In *Proceedings of the 15th international academic MindTrek conference: Envisioning future media environments.* 9–15.
[50] Carlos Díaz, Marisa Ponti, Pinja Haikka, Rajiv Basaiawmoit, and Jacob Sherson. 2020. More than data gatherers: exploring player experience in a citizen science game. *Quality and User Experience* 5, 1 (2020), 1.
[51] Scott Donaldson. 2017. Mechanics and metagame: Exploring binary expertise in league of legends. *Games and Culture* 12, 5 (2017), 426–444.
[52] Anders Drachen, Pejman Mirza-Babaei, and Lennart E Nacke. 2018. *Games user research.* Oxford University Press.
[53] Peter Eastman, Jade Shi, Bharath Ramsundar, and Vijay S Pande. 2018. Solving the RNA design problem with reinforcement learning. *PLoS computational biology* 14, 6 (2018), e1006176.
[54] Melissa V Eitzel, Jessica L Cappadonna, Chris Santos-Lang, Ruth Ellen Duerr, Arika Virapongse, Sarah Elizabeth West, Christopher Kyba, Anne Bowser, Caren Beth Cooper, Andrea Sforzi, et al. 2017. Citizen science terminology matters: Exploring key terms. *Citizen science: Theory and practice* 2, 1 (2017).
[55] Séverine Erhel and Eric Jamet. 2013. Digital game-based learning: Impact of instructions and feedback on motivation and learning effectiveness. *Computers & education* 67 (2013), 156–167.
[56] Alexandra Eveleigh, Charlene Jennett, Ann Blandford, Philip Brohan, and Anna L Cox. 2014. Designing for dabblers and deterring drop-outs in citizen science. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems.* ACM, 2985–2994.
[57] Alexandra Eveleigh, Charlene Jennett, Stuart Lynn, and Anna L Cox. 2013. "I want to be a captain! I want to be a captain!" gamification in the old weather citizen science project. In *Proceedings of the first international conference on gameful design, research, and applications.* 79–82.
[58] Travis Faas, Lynn Dombrowski, Alyson Young, and Andrew D Miller. 2018. Watch me code: Programming mentorship communities on twitch. tv. *Proceedings of the ACM on Human-Computer Interaction* 2, CSCW (2018), 1–18.
[59] Joey R Fanfarelli. 2018. Expertise in professional overwatch play. *International Journal of Gaming and Computer-Mediated Simulations (IJGCMS)* 10, 1 (2018), 1–22.
[60] Peter C Farley. 2013. Using the computer game "FoldIt" to entice students to explore external representations of protein structure in a biochemistry course for nonmajors. *Biochemistry and Molecular Biology Education* 41, 1 (2013), 56–57.
[61] Lucy Fortson, Karen Masters, Robert Nichol, EM Edmondson, C Lintott, J Raddick, and J Wallin. 2012. Galaxy zoo. *Advances in machine learning and data mining for astronomy* 2012 (2012), 213–236.
[62] Chiara Franzoni and Henry Sauermann. 2014. Crowd science: The organization of scientific research in open collaborative projects. *Research policy* 43, 1 (2014), 1–20.
[63] Matthew J Gaydos. 2013. *Design-based research and video game based learning: Developing the educational video game" Citizen Science".* Ph.D. Dissertation. The University of Wisconsin-Madison.
[64] James Paul Gee. 2003. What video games have to teach us about learning and literacy. *Computers in Entertainment (CIE)* 1, 1 (2003), 20–20.
[65] James Paul Gee. 2004. *An introduction to discourse analysis: Theory and method.* Routledge.
[66] James Paul Gee. 2005. Learning by design: Good video games as learning machines. *E-learning and Digital Media* 2, 1 (2005), 5–16.
[67] James Paul Gee. 2005. Semiotic social spaces and affinity spaces. *Beyond communities of practice language power and social context* 214232 (2005).
[68] James Paul Gee. 2007. *Good video games+ good learning: Collected essays on video games, learning, and literacy.* Peter Lang.
[69] James Paul Gee. 2015. Discourse, small d, big D. *The international encyclopedia of language and social interaction* 3 (2015), 1–5.
[70] CHRIS Georgen. 2015. Well played & well watched: Dota 2, spectatorship, and eSports. *Well Played A Journal on Video Games, Values, and Meaning* 4, 1 (2015), 179–191.
[71] Aytac Gogus. 2012. Peer Learning and Assessment. In *Encyclopedia of the Sciences of Learning*, Norbert M. Seel (Ed.). Springer US, Boston, MA, 2572–2576. https://doi.org/10.1007/978-1-4419-1428-6_146
[72] Charles Goodwin. 2015. Professional vision. In *Aufmerksamkeit.* Springer, 387–425.

[73] Anita Greenhill, Kate Holmes, Chris Lintott, Brooke Simmons, Karen Masters, Joe Cox, and Gary Graham. 2014. Playing with science: Gamised aspects of gamification found on the online citizen science project-zooniverse. In *GAMEON'2014*. EUROSIS, 15–24.

[74] Greg Guest, Arwen Bunce, and Laura Johnson. 2006. How many interviews are enough? An experiment with data saturation and variability. *Field methods* 18, 1 (2006), 59–82.

[75] Muki Haklay. 2013. Citizen Science and Volunteered Geographic Information: Overview and Typology of Participation. In *Crowdsourcing Geographic Knowledge*, Daniel Sui, Sarah Elwood, and Michael Goodchild (Eds.). Springer Netherlands, 105–122. https://doi.org/10.1007/978-94-007-4587-2_7

[76] Allison W Harrison, R Kelly Rainer Jr, Wayne A Hochwarter, and Kenneth R Thompson. 1997. Testing the self-efficacy—performance linkage of social—cognitive theory. *The Journal of social psychology* 137, 1 (1997), 79–87.

[77] Casper Harteveld. 2011. *Triadic game design: Balancing reality, meaning and play*. Springer Science & Business Media.

[78] Joshua K Hartshorne, Claire Bonial, and Martha Palmer. 2014. The VerbCorner Project: Findings from Phase 1 of crowd-sourcing a semantic decomposition of verbs. In *Proceedings of the 52nd Annual Meeting of the Association for Computational Linguistics (Volume 2: Short Papers)*. 397–402.

[79] Caroline Haythornthwaite. 2009. Crowds and communities: Light and heavyweight models of peer production. In *2009 42nd Hawaii international conference on system sciences*. IEEE, 1–10.

[80] Florian Heigl, Barbara Kieslinger, Katharina T Paul, Julia Uhlik, and Daniel Dörler. 2019. Opinion: Toward an international definition of citizen science. *Proceedings of the National Academy of Sciences* 116, 17 (2019), 8089–8092.

[81] Joseph Hesketh, Christoph Sebastian Deterding, and Jeremy Gow. 2020. How Players Learn Team-versus-Team Esports: First Results from A Grounded Theory Study. In *DiGRA'20 Abstract-Proceedings of the 2020 DiGRA International Conference*. York.

[82] Celia Hodent. 2017. *The gamer's brain: How neuroscience and UX can impact video game design*. CRC Press.

[83] Jeff Huang, Eddie Yan, Gifford Cheung, Nachiappan Nagappan, and Thomas Zimmermann. 2017. Master maker: Understanding gaming skill through practice and habit from gameplay behavior. *Topics in cognitive science* 9, 2 (2017), 437–466.

[84] Wenhao David Huang and Tristan Johnson. 2009. Instructional game design using cognitive load theory. In *Handbook of research on effective electronic gaming in education*. IGI Global, 1143–1165.

[85] Matthew Hyde, Maxwell Scott-Slade, Hugo Scott-Slade, Michael Hornberger, Hugo Spiers, Ruth Dalton, Christoph Hoelscher, Jan Wiener, and Veronique Bohbot. 2016. Sea Hero Quest: the World's first mobile game where anyone can help scientists fight dementia. (2016).

[86] Ioanna Iacovides, James C Aczel, Eileen Scanlon, and Will IS Woods. 2011. What can breakdowns and breakthroughs tell us about learning and involvement experienced during game-play. In *Proceedings of the 5th European Conference on Games Based Learning*. Academic Publishing International Reading, UK, 275–281.

[87] Ioanna Iacovides, Anna L Cox, Patrick McAndrew, James Aczel, and Eileen Scanlon. 2015. Game-play breakdowns and breakthroughs: exploring the relationship between action, understanding, and involvement. *Human–computer interaction* 30, 3-4 (2015), 202–231.

[88] Ioanna Iacovides, Charlene Jennett, Cassandra Cornish-Trestrail, and Anna L Cox. 2013. Do games attract or sustain engagement in citizen science?: a study of volunteer motivations. In *CHI'13 Extended Abstracts on Human Factors in Computing Systems*. ACM, 1101–1106.

[89] Ioanna Iacovides, Patrick McAndrew, Eileen Scanlon, and James Aczel. 2014. The gaming involvement and informal learning framework. *Simulation & gaming* 45, 4-5 (2014), 611–626.

[90] Charlene Jennett, Dominic J Furniss, Ioanna Iacovides, Sarah Wiseman, Sandy JJ Gould, and Anna L Cox. 2014. Exploring citizen psych-science and the motivations of errordiary volunteers. *Human Computation* 1, 2 (2014).

[91] Charlene Jennett, Laure Kloetzer, Daniel Schneider, Ioanna Iacovides, Anna Cox, Margaret Gold, Brian Fuchs, Alexandra Eveleigh, Kathleen Methieu, Zoya Ajani, et al. 2016. Motivations, learning and creativity in online citizen science. *Journal of Science Communication* 15, 3 (2016).

[92] Jesper Hasseriis Mohr Jensen, Miroslav Gajdacz, Shaeema Zaman Ahmed, Jakub Herman Czarkowski, Carrie Weidner, Janet Rafner, Jens Jakob Sørensen, Klaus Mølmer, and Jacob Friis Sherson. 2021. Crowdsourcing human common sense for quantum control. *Physical Review Research* 3, 1 (2021), 013057.

[93] Jae-Eun Jung and Yang-Hee Nam. 2015. Types of Gameplay Mechanics in Human Computation Games. *Journal of Korea Game Society* 15, 6 (2015), 157–170.

[94] Jesper Juul. 2011. *Half-real: Video games between real rules and fictional worlds*. MIT press.

[95] Slava Kalyuga and Jan L Plass. 2009. Evaluating and managing cognitive load in games. In *Handbook of research on effective electronic gaming in education*. IGI Global, 719–737.

[96] Alexander Kawrykow, Gary Roumanis, Alfred Kam, Daniel Kwak, Clarence Leung, Chu Wu, Eleyine Zarour, Luis Sarmenta, Mathieu Blanchette, Jérôme Waldispühl, et al. 2012. Phylo: a citizen science approach for improving multiple sequence alignment. *PloS one* 7, 3 (2012), e31362.

[97] Benjamin Ernest Keep. 2018. *Becoming Expert Problem Solvers: A Case Study in what Develops and how*. Ph.D. Dissertation. Stanford University.

[98] Ashley Rose Kelly and Kate Maddalena. 2015. Harnessing agency for efficacy:"Foldit" and citizen science. *Poroi* 11, 1 (2015), 1–20.

[99] Firas Khatib, Seth Cooper, Michael D Tyka, Kefan Xu, Ilya Makedon, Zoran Popović, and David Baker. 2011. Algorithm discovery by protein folding game players. *Proceedings of the National Academy of Sciences* 108, 47 (2011), 18949–18953.

[100] Louise H Kidder and Michelle Fine. 1987. Qualitative and quantitative methods: When stories converge. *New directions for program evaluation* 1987, 35 (1987), 57–75.

[101] Jeffrey Kim, Elan Lee, Timothy Thomas, and Caroline Dombrowski. 2009. Storytelling in new media: The case of alternate reality games, 2001–2009. *First Monday* (2009).

[102] Jinseop S Kim, Matthew J Greene, Aleksandar Zlateski, Kisuk Lee, Mark Richardson, Srinivas C Turaga, Michael Purcaro, Matthew Balkam, Amy Robinson, Bardia F Behabadi, et al. 2014. Space–time wiring specificity supports direction selectivity in the retina. *Nature* 509, 7500 (2014), 331–336.

[103] Robert Kleffner, Jeff Flatten, Andrew Leaver-Fay, David Baker, Justin B Siegel, Firas Khatib, and Seth Cooper. 2017. Foldit Standalone: a video game-derived protein structure manipulation interface using Rosetta. *Bioinformatics* 33, 17 (2017), 2765–2767.

[104] Eric Klopfer, Jason Haas, Scot Osterweil, and Louisa Rosenheck. 2018. *Resonant games: Design principles for learning games that connect hearts, minds, and the everyday*. MIT Press.

[105] Hannu Korhonen and Elina MI Koivisto. 2007. Playability heuristics for mobile multi-player games. In *Proceedings of the 2nd international conference on Digital interactive media in entertainment and arts*. ACM, 28–35.

[106] Jeff Kuhn. 2017. Minecraft: Education Edition. *calico journal* 35, 2 (2017), 214–223.

[107] Mathieu Lafourcade, Alain Joubert, and Nathalie Le Brun. 2015. Unclassifiable GWAPs. *Games with a Purpose (Gwaps)* (2015), 73–89.

[108] Anne Land-Zandstra, Gaia Agnello, and Yaşar Selman Gültekin. 2021. Participants in Citizen Science. *The Science of Citizen Science* (2021), 243.

[109] Jeehyung Lee, Wipapat Kladwang, Minjae Lee, Daniel Cantu, Martin Azizyan, Hanjoo Kim, Alex Limpaecher, Snehal Gaikwad, Sungroh Yoon, Adrien Treuille, et al. 2014. RNA design rules from a massive open laboratory. *Proceedings of the National Academy of Sciences* 111, 6 (2014), 2122–2127.

[110] Kisuk Lee. 2015. Crowd Intelligence in EyeWire. Technical report. Retrieved from http://kisuklee.wikidot.com/research#toc2 on May 6, 2021.

[111] Hjalti Leifsson and Jóhann Örn Bjarkason. 2015. *Project Discovery-Advancing scientific research by implementing citizen science in EVE Online*. Ph.D. Dissertation.

[112] Susan Leigh Star. 2010. This is not a boundary object: Reflections on the origin of a concept. *Science, Technology, & Human Values* 35, 5 (2010), 601–617.

[113] Jimmie Leppink, Fred Paas, Tamara Van Gog, Cees PM van Der Vleuten, and Jeroen JG Van Merrienboer. 2014. Effects of pairs of problems and examples on task performance and different types of cognitive load. *Learning and Instruction* 30 (2014), 32–42.

[114] Calvin A Liang, Sean A Munson, and Julie A Kientz. 2021. Embracing Four Tensions in Human-Computer Interaction Research with Marginalized People. *ACM Transactions on Computer-Human Interaction (TOCHI)* 28, 2 (2021), 1–47.

[115] Andreas Lieberoth, Mads Kock Pedersen, Andreea Catalina Marin, Tilo Planke, and Jacob Friis Sherson. 2015. Getting humans to do quantum optimization-user acquisition, engagement and early results from the citizen cyberscience game Quantum Moves. *arXiv preprint arXiv:1506.08761* (2015).

[116] Jung Lim, Robert A Reiser, and Zane Olina. 2009. The effects of part-task and whole-task instructional approaches on acquisition and transfer of a complex cognitive skill. *Educational Technology Research and Development* 57, 1 (2009), 61–77.

[117] Chun-Yi Lin and Charles M Reigeluth. 2019. Scaffolding learner autonomy in a wiki-supported knowledge building community and its implications for mindset change. *British Journal of Educational Technology* 50, 5 (2019), 2667–2684.

[118] Shlomit Aharoni Lir. 2019. Strangers in a seemingly open-to-all website: the gender bias in Wikipedia. *Equality, Diversity and Inclusion: An International Journal* (2019).

[119] Jacqueline Low. 2019. A pragmatic definition of the concept of theoretical saturation. *Sociological Focus* 52, 2 (2019), 131–139.

[120] Miguel Angel Luengo-Oroz, Asier Arranz, and John Frean. 2012. Crowdsourcing malaria parasite quantification: an online game for analyzing images of infected thick blood smears. *Journal of medical Internet research* 14, 6 (2012), e167.

[121] Colleen Macklin and John Sharp. 2016. *Games, design and play: a detailed approach to iterative game design* (first edition ed.). Addison-Wesley, Boston, MA ; San Francisco, CA.

[122] Vivien Marx. 2013. Neuroscience waves to the crowd. *Nature methods* 10, 11 (2013), 1069–1074.
[123] Benedict McAteer, Wesley Flannery, and Brendan Murtagh. 2021. Linking the motivations and outcomes of volunteers to understand participation in marine community science. *Marine Policy* 124 (2021), 104375.
[124] Josh Aaron Miller, Britton Horn, Matthew Guthrie, Jonathan Romano, Guy Geva, Celia David, Amy Robinson Sterling, and Seth Cooper. 2021. How do Players and Developers of Citizen Science Games Conceptualize Skill Chains?. In *Proceedings of the Annual Symposium on Computer-Human Interaction in Play (CHI PLAY '21)*. Association for Computing Machinery, New York, NY, USA, in press. https://doi.org/10.1145/3474671
[125] Josh Aaron Miller, Vivian Lee, Seth Cooper, and Magy Seif El-Nasr. 2019. Large-Scale Analysis of Visualization Options in a Citizen Science Game. In *Extended Abstracts of the Annual Symposium on Computer-Human Interaction in Play Companion Extended Abstracts*. 535–542.
[126] Briana B Morrison and Betsy DiSalvo. 2014. Khan academy gamifies computer science. In *Proceedings of the 45th ACM technical symposium on Computer science education*. 39–44.
[127] Benedikt Morschheuser, Juho Hamari, and Jonna Koivisto. 2016. Gamification in crowdsourcing: a review. In *2016 49th Hawaii International Conference on System Sciences (HICSS)*. IEEE, 4375–4384.
[128] Benedikt Morschheuser, Juho Hamari, Jonna Koivisto, and Alexander Maedche. 2017. Gamified crowdsourcing: Conceptualization, literature review, and future agenda. *International Journal of Human-Computer Studies* 106 (2017), 26–43.
[129] Andrew Murphy. 2020. A Gamer's Guide to Eterna. Retrieved from https://www.keystone-research-solutions.com/en/item/a-gamers-guide-to-eterna on November 29, 2021.
[130] Greg Newman, Andrea Wiggins, Alycia Crall, Eric Graham, Sarah Newman, and Kevin Crowston. 2012. The future of citizen science: emerging technologies and shifting paradigms. *Frontiers in Ecology and the Environment* 10, 6 (2012), 298–304.
[131] Jakob Nielsen. 1994. Enhancing the explanatory power of usability heuristics. In *Proceedings of the SIGCHI conference on Human Factors in Computing Systems*. ACM, 152–158.
[132] Donald A Norman and Stephen W Draper. 1986. User centered system design: New perspectives on human-computer interaction. (1986).
[133] Jill Nugent. 2018. iNaturalist: citizen science for 21st-century naturalists. *Science Scope* 41, 7 (2018), 12.
[134] Janne Paavilainen. 2010. Critical Review on Video Game Evaluation Heuristics: Social Games Perspective. In *Proceedings of the International Academic Conference on the Future of Game Design and Technology* (Vancouver, British Columbia, Canada) *(Futureplay '10)*. ACM, New York, NY, USA, 56–65. https://doi.org/10.1145/1920778.1920787
[135] Janne Paavilainen. 2020. Defining playability of games: functionality, usability, and gameplay. In *Proceedings of the 23rd International Conference on Academic Mindtrek*. 55–64.
[136] Carole Paleco, Sabina García Peter, Nora Salas Seoane, Julia Kaufmann, and Panagiota Argyri. 2021. Inclusiveness and Diversity in Citizen Science. *The Science of Citizen Science* (2021), 261.
[137] Mads Kock Pedersen, Carlos Mauricio Castaño Díaz, Mario Alejandro Alba-Marrugo, Ali Amidi, Rajiv Vaid Basaiawmoit, Carsten Bergenholtz, Morten H Christiansen, Miroslav Gajdacz, Ralph Hertwig, Byurakn Ishkhanyan, et al. 2020. Cognitive Abilities in the Wild: Population-scale game-based cognitive assessment. *arXiv preprint arXiv:2009.05274* (2020).
[138] David Pinelle, Nelson Wong, Tadeusz Stach, and Carl Gutwin. 2009. Usability heuristics for networked multiplayer games. In *Proceedings of the ACM 2009 international conference on Supporting group work*. ACM, 169–178.
[139] Lesandro Ponciano and Francisco Brasileiro. 2015. Finding volunteers' engagement profiles in human computation for citizen science projects. *arXiv preprint arXiv:1501.02134* (2015).
[140] Marisa Ponti, Thomas Hillman, Christopher Kullenberg, and Dick Kasperowski. 2018. Getting it right or being top rank: Games in citizen science. *Citizen Science: Theory and Practice* 3, 1 (2018).
[141] Marisa Ponti, Igor Stankovic, Wolmet Barendregt, Bruno Kestemont, and Lyn Bain. 2018. Chefs know more than just recipes: professional vision in a citizen science game. *Human Computation* 5 (2018), 1–12.
[142] Fernando Portela. 2018. An unexpectedly effective Monte Carlo technique for the RNA inverse folding problem. *BioRxiv* (2018), 345587.
[143] Nathan Prestopnik and Kevin Crowston. 2012. Purposeful gaming & socio-computational systems: a citizen science design case. In *Proceedings of the 17th ACM international conference on Supporting group work*. 75–84.
[144] Nathan Prestopnik, Kevin Crowston, and Jun Wang. 2014. Exploring data quality in games with a purpose. *iConference 2014 Proceedings* (2014).
[145] Nathan Prestopnik and Dania Souid. 2013. Forgotten island: a story-driven citizen science adventure. In *CHI'13 Extended Abstracts on Human Factors in Computing Systems*. 2643–2646.
[146] Nathan R Prestopnik and Kevin Crowston. 2012. Citizen science system assemblages: understanding the technologies that support crowdsourced science. In *Proceedings of the 2012 iConference*. 168–176.
[147] Nathan R Prestopnik and Jian Tang. 2015. Points, stories, worlds, and diegesis: Comparing player experiences in two citizen science games. *Computers in Human Behavior* 52 (2015), 492–506.
[148] Yu Qi Qiao, Jun Shen, Xiao Liang, Song Ding, Fang Yuan Chen, Li Shao, Qing Zheng, and Zhi Hua Ran. 2014. Using cognitive theory to facilitate medical education. *BMC medical education* 14, 1 (2014), 79.
[149] Chris Quintana, Brian J Reiser, Elizabeth A Davis, Joseph Krajcik, Eric Fretz, Ravit Golan Duncan, Eleni Kyza, Daniel Edelson, and Elliot Soloway. 2004. A scaffolding design framework for software to support science inquiry. *The journal of the learning sciences* 13, 3 (2004), 337–386.
[150] M Jordan Raddick, Georgia Bracey, Pamela L Gay, Chris J Lintott, Carie Cardamone, Phil Murray, Kevin Schawinski, Alexander S Szalay, and Jan Vandenberg. 2013. Galaxy Zoo: Motivations of citizen scientists. *arXiv preprint arXiv:1303.6886* (2013).
[151] Janet Rafner, Miroslav Gajdacz, Gitte Kragh, Arthur Hjorth, Anna Gander, Blanka Palfi, Aleks Berditchevskaia, François Grey, Kobi Gal, Avi Segal, et al. 2021. Revisiting Citizen Science Through the Lens of Hybrid Intelligence. *arXiv preprint arXiv:2104.14961* (2021).
[152] Tzipora Rakedzon, Elad Segev, Noam Chapnik, Roy Yosef, and Ayelet Baram-Tsabari. 2017. Automatic jargon identifier for scientists engaging with the public and science communication educators. *PloS one* 12, 8 (2017), e0181742.
[153] Neal Reeves, Peter West, and Elena Simperl. 2018. A game without competition is hardly a game": The impact of competitions on player activity in a human computation game. In *Sixth AAAI Conference on Human Computation and Crowdsourcing*.
[154] C Reigeluth and R Stein. 1983. Elaboration theory. *Instructional-design theories and models: An overview of their current status (1983)* (1983), 335–381.
[155] Dana Rotman, Jenny Preece, Jen Hammock, Kezee Procita, Derek Hansen, Cynthia Parr, Darcy Lewis, and David Jacobs. 2012. Dynamic changes in motivation in collaborative citizen-science projects. In *Proceedings of the ACM 2012 conference on computer supported cooperative work*. 217–226.
[156] Thomas A Rowles. 2013. Power to the people: Does Eterna signal the arrival of a new wave of crowd-sourced projects?
[157] Simone Rüfenacht, Tim Woods, Gaia Agnello, Margaret Gold, Philipp Hummer, Anne Land-Zandstra, and Andrea Sieber. 2021. Communication and Dissemination in Citizen Science. *The Science of Citizen Science* (2021), 475.
[158] Fredrik Rusk, Matilda Ståhl, and Kenneth Silseth. 2020. Exploring Peer Mentoring and Learning Among Experts and Novices in Online in-Game Interactions. In *Proceedings of the 14th International Conference on Game Based Learning, ed. P. Fotaris*. 461–468.
[159] Katie Salen, Katie Salen Tekinbaş, and Eric Zimmerman. 2004. *Rules of play: Game design fundamentals*. MIT press.
[160] Henrik Schoenau-Fog. 2011. The Player Engagement Process-An Exploration of Continuation Desire in Digital Games.. In *Proceedings of the DiGRA Conference*.
[161] Karen Schrier. 2016. *Knowledge games: How playing games can solve problems, create insight, and make change*. JHU Press.
[162] Karen Schrier. 2017. Investigating typologies of games as research environments. In *Proceedings of International Conference on the Foundations of Digital Games*. 1–4.
[163] Dale H Schunk. 2012. *Learning theories an educational perspective sixth edition*. Pearson.
[164] Daniel L Schwartz and John D Bransford. 1998. A time for telling. *Cognition and instruction* 16, 4 (1998), 475–5223.
[165] Hortense Serret, Nicolas Deguines, Yikweon Jang, Grégoire Lois, and Romain Julliard. 2019. Data quality and participant engagement in citizen science: comparing two approaches for monitoring pollinators in France and South Korea. *Citizen Science: Theory and Practice* 4, 1 (2019), 22.
[166] Mike Sharples. 2009. Methods for evaluating mobile learning. *Researching mobile learning: Frameworks, tools and research designs* (2009), 17–39.
[167] Jennifer L Shirk, Heidi L Ballard, Candie C Wilderman, Tina Phillips, Andrea Wiggins, Rebecca Jordan, Ellen McCallie, Matthew Minarchek, Bruce V Lewenstein, Marianne E Krasny, et al. 2012. Public participation in scientific research: a framework for deliberate design. *Ecology and society* 17, 2 (2012).
[168] Hillary C Shulman, Graham N Dixon, Olivia M Bullock, and Daniel Colón Amill. 2020. The effects of jargon on processing fluency, self-perceptions, and scientific engagement. *Journal of Language and Social Psychology* 39, 5-6 (2020), 579–597.
[169] Nyet Moi Siew, Jolly Geofrey, and Bih Ni Lee. 2016. Students' algebraic thinking and attitudes towards algebra: the effects of game-based learning using Dragonbox 12+ App. *The Research Journal of Mathematics and Technology* 5, 1 (2016), 66–79.
[170] Artemis Skarlatidou, Alexandra Hamilton, Michalis Vitos, and Muki Haklay. 2019. What do volunteers want from citizen science technologies? A systematic literature review and best practice guidelines. *JCOM: Journal of Science Communication* 18, 1 (2019).
[171] Helen Spiers, Alexandra Swanson, Lucy Fortson, Brooke Simmons, Laura Trouille, Samantha Blickhan, and Chris Lintott. 2019. Everyone counts? Design considerations in online citizen science. *Journal of Science Communication* 18, 1

(2019).
[172] Kurt Squire. 2012. Designed Cultures. In *Games, learning, and society: Learning and meaning in the digital age*, Constance Steinkuehler, Kurt Squire, and Sasha Barab (Eds.). Cambridge University Press, Chapter 2.
[173] Penelope Sweetser and Peta Wyeth. 2005. GameFlow: a model for evaluating player enjoyment in games. *Computers in Entertainment (CIE)* 3, 3 (2005), 3–3.
[174] John Sweller. 2011. Cognitive load theory. In *Psychology of learning and motivation*. Vol. 55. Elsevier, 37–76.
[175] Nick Paul Taylor. 2016. Gamers crush algorithms in RNA structure design challenge. https://www.fiercebiotech.com/r-d/gamers-crush-algorithms-rna-structure-design-challenge
[176] Joseph J Thompson, Mark R Blair, Lihan Chen, and Andrew J Henrey. 2013. Video game telemetry as a critical tool in the study of complex skill learning. *PloS one* 8, 9 (2013), e75129.
[177] Ramine Tinati, Markus Luczak-Roesch, Elena Simperl, and Wendy Hall. 2016. Because science is awesome: studying participation in a citizen science game. In *Proceedings of the 8th ACM Conference on Web Science*. 45–54.
[178] Ramine Tinati, Markus Luczak-Roesch, Elena Simperl, and Wendy Hall. 2017. An investigation of player motivations in Eyewire, a gamified citizen science project. *Computers in Human Behavior* 73 (2017), 527–540.
[179] Keith Topping and Stewart Ehly. 1998. *Peer-assisted learning*. Routledge.
[180] Kathleen Tuite. 2014. GWAPs: Games with a problem.. In *FDG*.
[181] TV Tropes contributors. 2020. Golden Path. Retrieved from https://tvtropes.org/pmwiki/pmwiki.php/Main/GoldenPath on January 5, 2021.
[182] AlzheimersResearch UK. 2017. Sea Hero Quest VR - Walkthrough Video. Retrieved from https://www.youtube.com/watch?v=CcM6Yu9d4pM on December 2, 2021.
[183] U.S. General Services Administration. 2018. EyeWire | A Game to Crowdsource Brain Mapping. https://www.citizenscience.gov/eyewire-brain-mapping/#
[184] Krishna Teja Vaddepalli. 2019. Improving data quality in citizen science. (2019).
[185] Jeroen JG Van Merriënboer. 1997. *Training complex cognitive skills: A four-component instructional design model for technical training*. Educational Technology.
[186] Jeroen JG Van Merriënboer, Otto Jelsma, and Fred GWC Paas. 1992. Training for reflective expertise: A four-component instructional design model for complex cognitive skills. *Educational Technology Research and Development* 40, 2 (1992), 23–43.
[187] Jeroen JG Van Merriënboer and Liesbeth Kester. 2008. Whole-task models in education. *Handbook of research on educational communications and technology* 3 (2008), 441–456.
[188] Jeroen JG Van Merriënboer and Liesbeth Kester. 2014. The four-component instructional design model: Multimedia principles in environments for complex learning. (2014).
[189] Jeroen JG Van Merriënboer and Paul A Kirschner. 2017. *Ten steps to complex learning: A systematic approach to four-component instructional design*. Routledge.
[190] Jeroen JG Van Merriënboer and Dominique MA Sluijsmans. 2009. Toward a synthesis of cognitive load theory, four-component instructional design, and self-directed learning. *Educational Psychology Review* 21, 1 (2009), 55–66.
[191] Carina Maria Veeckman, Sarah Talboom, Liesbeth Gijsel, Hilde Devoghel, and Annelies Duerinckx. 2019. Communicatie bij burgerwetenschap: Een praktische handleiding voor communicatie en betrokkenheid bij citizen science. (2019).
[192] Jérôme Waldispühl, Attila Szantner, Rob Knight, Sébastien Caisse, and Randy Pitchford. 2020. Leveling up citizen science. *Nature Biotechnology* 38, 10 (2020), 1124–1126.
[193] Chih-Chien Wang and Yi-Shiu Chu. 2007. Harmonious passion and obsessive passion in playing online games. *Social Behavior and Personality: an international journal* 35, 7 (2007), 997–1006.
[194] Sarah Elizabeth West and Rachel Mary Pateman. 2016. Recruiting and retaining participants in citizen science: What can be learned from the volunteering literature? *Citizen Science: Theory and Practice* (2016).
[195] Matthew M White. 2014. *Learn to Play: Designing Tutorials for Video Games*. CRC Press.
[196] Andrea Wiggins and Kevin Crowston. 2011. From conservation to crowdsourcing: A typology of citizen science. In *2011 44th Hawaii international conference on system sciences*. IEEE, 1–10.
[197] Andrea Wiggins and Kevin Crowston. 2015. Surveying the citizen science landscape. *First Monday* (2015).
[198] James Wootton. 2017. Decodoku: Quantum error rorrection as a simple puzzle game. In *APS March Meeting Abstracts*, Vol. 2017. V27–010.
[199] James R Wootton. 2017. Getting the public involved in Quantum Error Correction. *arXiv preprint arXiv:1712.09649* (2017).
[200] Binbin Zheng, Melissa Niiya, and Mark Warschauer. 2015. Wikis and collaborative learning in higher education. *Technology, Pedagogy and Education* 24, 3 (2015), 357–374.