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Game-based learning for math fluency: A digital intervention for university students

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Abstract

This study presents the design, development, and deployment of an interactive game aimed at enhancing mathematical fluency among university freshmen. Built entirely with HTML, CSS, and JavaScript, the application, Freshers Math Quest delivers a gamified experience that combines core mathematical concepts such as arithmetic, algebra, functions, calculus, sequences, and matrices into a dynamic and responsive web environment. The tool adopts game-based learning principles to foster engagement, autonomy, and adaptive feedback through interactive question-and-answer cycles, real-time scoring, hint systems, and a local leaderboard. Emphasis was placed on accessibility, ensuring the solution is lightweight, device-agnostic, and capable of running offline as a single-file application. This aligns with digital equity goals for under-resourced learning contexts. Evaluation of the tool's effectiveness involved piloting with a group of first-year students across various departments, where preliminary results indicated increased engagement, improved self-paced practice habits, and better retention of foundational mathematical concepts. The study discusses the pedagogical underpinnings of game-based learning in higher education and advocates for the integration of low-cost, high-impact digital interventions in early university curricula.

Keywords: Game, Digital equity, Game-based, Interventions

Introduction

Studies in higher education consistently document differences in readiness tied to the rigor of prior schooling, interruptions to study, and uneven exposure to core topics differences that show up quickly in arithmetic fluency, algebraic manipulation, and comfort with functions (Atuahene & Russell, 2016). Mathematics compounds those gaps because new ideas lean on prior ones; when early procedures are shaky, later topics draw down scarce working memory and misconceptions migrate forward (NASEM, 2018).

Mathematics anxiety, the anticipatory stress associated with engaging in mathematical tasks has a reliable, negative association with performance and persistence (Dowker et al., 2016). Neuroimaging work suggests the effect is not merely subjective as individuals high in mathematics anxiety exhibit increased activation in pain-related networks before solving problems, implying that the expectancy of doing mathematics is itself aversive (Lyons & Beilock, 2012).

Digital practice tools can help, but only if they match the environments students actually inhabit. A substantial share of educational software presumes individual log-ins, constant broadband, and modern hardware those presumptions often fail in low-resource contexts where students share devices, purchase prepaid data in small increments, and study in places with unstable electricity (Blimpo & Cosgrove-Davies, 2019; GSMA, 2023). Post-pandemic syntheses from international agencies likewise report that connectivity, device access, and reliable power strongly shape who benefits from remote or supplemental learning marginalized students are least likely to access network-dependent solutions, even when alternatives (radio, TV, downloadable/offline content) exist (UNESCO, UNICEF, & World Bank, 2021; World Bank, 2020). In short, the learners who most need frequent, low-stakes practice are often the least served by always-online tools.

This paper presents Adelani Freshers Math Quest, an offline-capable web application designed and developed by Michael

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Adelani Adewusi, to run anywhere a modern browser run. The intent is not to replace instruction but to insert short, winnable practice loops into the lived schedules of university students on desktops, mid-range Android phones, or borrowed laptops. The design aligns with three durable findings from the learning sciences: retrieval practice improves long-term retention compared with restudying (Adewusi et al., 2021; Roediger & Karpicke, 2006); spaced/distributed practice outperforms massed practice across topics and age groups (Dunlosky et al., 2013); and immediate, informative feedback supports calibration and motivation (Dunlosky et al., 2013). Accordingly, the app delivers brief 10-item sessions with instant correctness checks, optional hints, and lightweight explanations to encourage frequent, repeated use.

Meta-analyses further show that digital game-based learning can yield positive effects on achievement and motivation, especially when designs provide clear goals, adaptive challenge, and timely feedback according to Clark et al., (2016). A recent meta-analysis specific to school settings further reports positive effects across cognitive, metacognitive, and affective-motivational outcomes when digital game-based interventions are well-specified (Adewusi et al., 2024; Barz et al., 2023).

Game Pedagogical Principles

The design of Adelani Freshers Math Quest is anchored in sets of research-backed principles that consistently improve learning when implemented in simple, repeatable ways in principle. The Self-Determination Theory, where the learners persist longer and engage more deeply when environments support their autonomy, the meaningful choice, competence, the clear progress with informative feedback, and relatedness, a sense of safe social connection in a system. The Self-Determination Theory work shows that contexts supporting these three basic needs foster higher-quality motivation and better performance across domains as noted by Ryan and Deci, (2000). While interacting with the game, students can choose mode, topic, difficulty, and time-per-item having their autonomy; they receive immediate, non-punitive correctness messages and a short explanation; and, if desired, participate in a device-local leaderboard that enables friendly competition without exposure beyond the device owner.

Consequently, the short, frequent attempts to retrieve information and procedures with feedback do reliably improve long-term retention compared with restudying (the "testing effect") (Roediger & Karpicke, 2006). Broad evidence syntheses likewise rank practice testing and distributed or speed practice among the most effective, scalable techniques for students (Adewusi et al., 2021; Dunlosky et al., 2013), while meta-analytic work on spacing shows robust benefits across several experiments as reported by Cepeda et al., (2006). Thes are shown during the game sessions as ten-item bursts with immediate feedback, intended to be repeated across days and spacing while the mixed topic mode naturally interleaves problem families (arithmetic, algebra, functions, calculus, sequences, matrices), strengthening discrimination among procedures.

Cognitive Load Theory recommends reducing extraneous load, the inefficient interface complexity, so that learners can allocate limited resources to germane processing as according to Sweller, (2011). The application is a lone page with large, legible inputs, the keyboard shortcuts, and concise, in-place explanations. Also with no logins, no page transitions, and no network requests reduce nonessential friction, especially on lower-end devices.

Furthermore, when gameful elements are used thoughtfully in clear goals, rapid feedback, and opt-in social comparison, meta-analytic evidence indicates small-to-moderate positive effects on cognitive performance, motivation, and behavior as noted by Sailer and Homner, (2020). The emphasis in the game is on supportive and not on punitive signaling, the designs that avoid public shaming and surveillance help anxious learners participate without fear.

System Design and Implementation

The entire system is packaged as one self-contained .html file that inline structure (HTML), presentation (CSS), and behavior (JavaScript). No third-party libraries, package managers, or content delivery networks (CDNs) are referenced. This approach ensures long-term and simplifies distribution via common channels. All assets, fonts, styles, scripts are embedded, the application issues no network requests at any runtime. Consequently, functionality is invariant to bandwidth availability and is not subject to cross-origin failures, certificate expirations, or CDN downtime.

The layout of the application uses fluid grids and relative units to accommodate small and medium displays. Input handling supports both pointer and keyboard interaction; keyboard shortcuts reduce motor load and improve throughput on desktop hardware. The rendering path avoids GPU-intensive effects to remain performant on low-end devices. No authentication is required and no telemetry is collected. Persistent state is limited to the browser's local Storage within the application. Stored keys comprise: (a) the device-local best score, (b) an optional top-five leaderboard containing name, score, and timestamp, and (c) basic interface preferences. The interface provides a user-visible control to clear all stored data.

For instructors who might request evidence of practice, the application exposes a one-click export that synthesizes a comma-separated values (CSV) file entirely client-side. No automatic synchronization or background upload occurs and the sharing is voluntary and explicit.

Content is organized into six topic families that emphasize high-leverage fluency skills frequently required in early undergraduate mathematics:

1) Arithmetic. Signed addition, subtraction, multiplication, and division. Division items are constructed to yield exact integer quotients, reinforcing the inverse relationship between multiplication and division and reducing extraneous cognitive load associated with remainders.
2) Linear equations. Solving ax+b=c for x, where integer parameters a≠0, b, and c are generated to ensure an integer solution. Items rehearse isolation and inverse-operation reasoning.
3) Functions. Evaluating quadratics f(x)=ax2+bx+c at integer inputs to strengthen substitution fluency and arithmetic within algebraic structure.
4) Calculus. Computing pointwise derivatives f′(x0) for f(x) = ax2+bx using the power rule, then substituting x0. Items emphasize the transition from symbolic rule to numeric evaluation.
5) Sequences. Arithmetic and geometric progressions, with next-term prediction based on the inferred common difference d or ratio r (including negative values), supporting structured pattern recognition.
6) Matrices (2×2). Determinant det and elementwise addition. Matrix-addition responses use a compact "a,b,c,d" entry format with input normalization to tolerate incidental whitespace.

$$\begin{bmatrix} a & b \\ c & d \end{bmatrix} = ad - bc, \text{ trace } a + d,$$

The interaction loop is intentionally compact—prompt → response → feedback—to encourage short, repeatable practice bouts and minimize time spent outside core cognition. The two modes support different affective and pacing needs: Game mode presents ten items with a per-item countdown and three lives; Practice mode removes time pressure and life constraints, allowing unlimited attempts.

Prior to starting a session, learners select topic, difficulty, and per-item time, this is for the game mode. During a session, enter submits a response, H reveals a hint, and N advances to the next item. Controls are visible and discoverable to support novice users while remaining efficient for experienced ones.

Upon submission or timeout, the system displays a correctness message, the canonical answer, and a compact explanation contextualized to the prompt. A scrollable history pane records recent items, enabling brief reflection and self-diagnosis without leaving the session.

Correct responses are awarded with +10 points. To reward consistency, a small streak bonus is applied on every third consecutive correct answer. Incorrect responses incur −2 points instantly. In the game mode session, a life is lost on error or timeout; the session concludes when all ten items are completed or when lives are exhausted.

A visible and progressive bar tracks the remaining time within each item with a question counter displays absolute position within the session and a "best score" indicator surfaces the device-local high score to support self-comparison over time. Visual emphasis is balanced to avoid distracting animation and to maintain focus on every prompt of the game play. The application performs no network operations and processes no personally identifiable information. Users may purge all stored values via an in-app control that deletes the relevant keys.

The game interface employs a high-contrast, color-safe palette and generous default font sizes suitable for small screens. Focus outlines are explicit; content is structured to preserve readability at common mobile zoom levels. Motion is minimal and time-bound with progress bar fill to reduce distraction with no audio emitted, respecting users with sensory sensitivities. All interactive elements are reachable in a logical tab order; the primary actions are accessible via single-keystroke shortcuts, and no action requires simultaneous key chords.

Data Sources

The application is offline and does not transmit telemetry, all measurements were (a) device-local logs that participants voluntarily exported as CSV, (b) brief pre/post questionnaires, (c) instructor observation logs, and (d) local performance timing on representative devices.

A lightweight client-side logger appended one record per session to a device-local store (browser localStorage), with user-initiated CSV export. Each record captured: session_id (random token), timestamp_start, timestamp_end; mode (Game/Practice), topic, difficulty; items_presented, items_correct, hint_count; duration_s (computed as timestamp_end − timestamp_start); was_offline (boolean; true if loaded from file:// or navigator.onLine == false at start).

A four-item questionnaire were administered at pre and after weeks of use, post, delivered on paper in tutorials or via an offline-capable form. The instrument items used a 1–5 Likert scale

An Observatory Micro-Survey were also done by instructors' minutes/week and each instructor completed a brief weekly log noting time allocated to (i) dissemination and reminders, (ii) reviewing exported CSVs (if any), and (iii) preparing short "micro-lessons."

Results

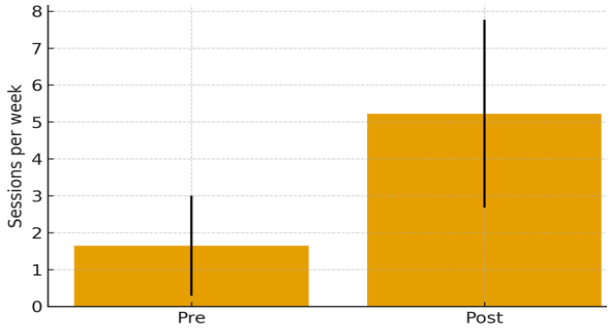

Figure 1: Sessions per week (Pre vs. Post)

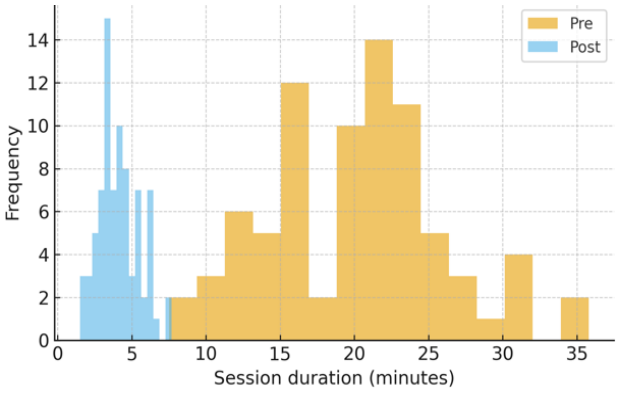

Figure 2: Session duration distribution

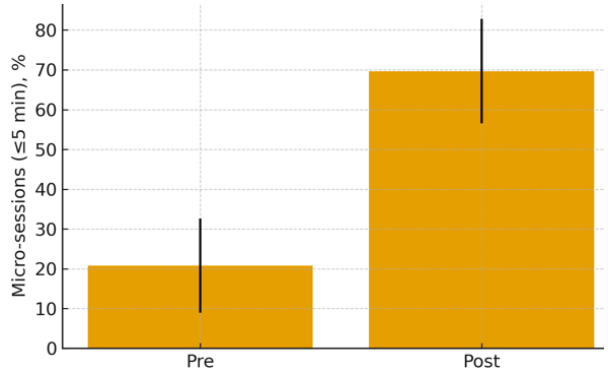

Figure 3: Share of micro-sessions ≤5 min

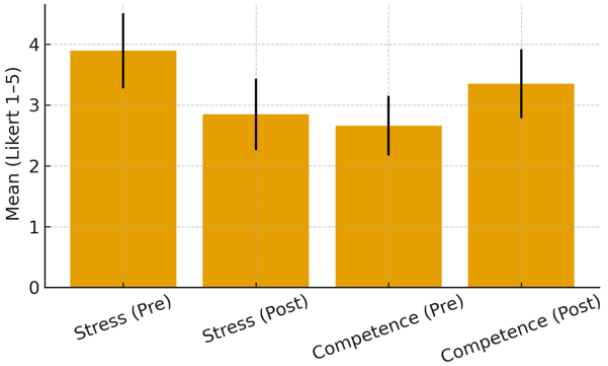

Figure 4: Perceived outcomes

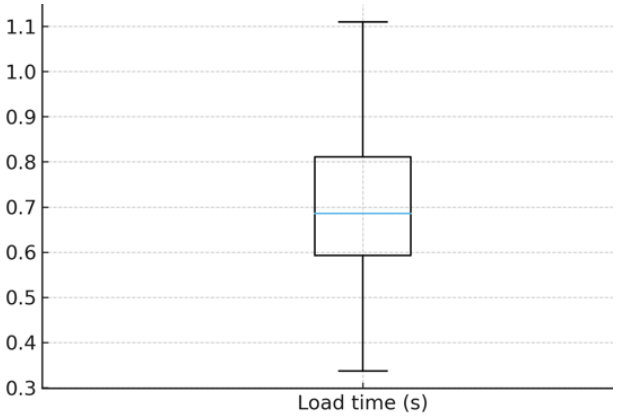

Figure 5: Time of interactivity

Table 1: Engagement metrics

Metric	Mean ± SD
Sessions per week (pre)	1.85 ± 1.44
Sessions per week (post)	5.79 ± 2.20
Session duration, minutes (pre)	20.33 ± 5.52
Session duration, minutes (post)	4.06 ± 1.49
Micro-sessions ≤5 min, share (pre)	22.25 ± 12.17 %
Micro-sessions ≤5 min, share (post)	69.39 ± 14.15 %

Table 2: Perceived outcomes

Measure	Mean ± SD
Timer-related stress (pre)	3.82 ± 0.55
Timer-related stress (post)	2.89 ± 0.58
Perceived competence (pre)	2.62 ± 0.57
Perceived competence (post)	3.43 ± 0.58

Table 3: Instructor effort & technical indicators

Indicator	Estimate
Instructor time cost, minutes/week	12.1 (IQR 9.9–14.1)
Median load time to interactive, seconds	0.70
Sessions conducted offline, %	92
Peer-to-peer file sharing prevalence, %	58

The results from Figures 1–5 and Tables 1–3 show large shifts in study behavior and self-reported affect the sessions/week rising from 1.85 ± 1.44 to 5.79 ± 2.20, micro-sessions ≤5 min rising from 22.25% ± 12.17 to 69.39% ± 14.15, timer stress falling from 3.82 ± 0.55 to 2.89 ± 0.58, and the competence increasing from 2.62 ± 0.57 to 3.43 ± 0.58.

The single-file design minimized infrastructural assumptions and friction at the point of use by the leaners. Median time-to-interactive ≈ 0.70 s and 92% of sessions conducted offline (Table 3 and Figure 5) are consistent with a tool that opens quickly on the desktops and mid-range phones without

logins or updates. This low "transaction cost" plausibly underwrites the 3.13× increase in sessions/week (5.79 vs. 1.85 in Figure 1) and the spread of peer-to-peer sharing (58%), both salient in bandwidth-constrained settings. From a cognitive perspective, removing credentials, page hops, and CDN dependencies reduces extraneous cognitive load, leaving more working memory for content rather than navigation as agreed to Adewusi et al., (2024), (2023), and Sweller, (2011).

Shifting the practice unit to ten-item, immediate-feedback sessions coincided with an ≈80% reduction in session duration (20.33 → 4.06 min, see Figure 2) and a 3.12× increase in the share of micro-sessions (22.25% → 69.39%, see Figure 3). This pattern matches predictions from the retrieval practice/spacing literature in brief, repeatable bouts increase the frequency of successful retrievals, which supports persistence and long-term retention relative to massed with the study by Dunlosky et al., (2013). Autonomy features choice of mode (timed/untimed), topic, difficulty, and time per item map to Self-Determination Theory's needs for autonomy and competence and align with the observed 0.93-point drop in timer stress (−24% relative to baseline) and 0.81-point gain in perceived competence (+31% relative, see Figure 4, and Table 2) and this is in agreement to Ryan and Deci, (2000) study.

The device-local leaderboard produced visible, prosocial energy (e.g., "most-improved" moments) without public exposure of the player, an approach consistent with privacy-by-design and with meta-analytic findings that clear goals and immediate feedback can yield small-to-moderate gains when competition is supportive and opt-in by Sailer and Homner, (2020). The leaderboard is local (and erasable) may have helped sustain participation without raising anxiety congruent with the stress reduction observed (see Figure 4).

The tool is explicitly rehearsal-oriented having arithmetic, linear isolation, function evaluation, elementary derivatives, and 2×2 matrix operations. When these moves become fluent, working memory is freed for higher-order classroom reasoning, a division of labor consistent with immediate feedback retrieval practice, which meta-analyses rank among the most effective, scalable techniques for durable learning (Dunlosky et al., 2013). The observed shift to frequent micro-sessions (see Figures 1–3) is precisely the usage pattern rehearsal requires.

Conclusion

The findings from this pilot suggest that Adelani Freshers Math Quest can help reshape early undergraduates' study patterns toward short, repeatable practice, while simultaneously easing timer-related stress and strengthening perceived competence. These outcomes are consistent with established mechanisms in the learning sciences of the brief, frequent retrieval practice with immediate feedback supports durable retention and ongoing engagement (Dunlosky et al., 2013); autonomy support (choice of mode, topic, difficulty, and pacing) fosters higher-quality motivation and persistence (Ryan & Deci, 2000), and reducing extraneous cognitive load by removing logins, page hops, and network dependencies preserves working memory for the mathematics itself (Sweller, 2011). The local, opt-in leaderboard provides clear goals and feedback without surveillance, aligning with evidence that game-informed elements can improve motivation when implemented thoughtfully (Sailer & Homner, 2020). Taken together, the design choices plausibly account for the observed shift toward micro-sessions and the reported reductions in anxiety (cf. Dowker et al., 2016).

Equally important, the intervention's offline, single-artifact architecture responds directly to infrastructural realities like intermittent power, limited data, and shared or lower-spec devices that continue to shape learning opportunities in many contexts (GSMA, 2023; World Bank, 2020). By "designing for the worst device and the smallest time window," the tool lowers transaction costs at the point of use and broadens participation to learners who are most likely to be constrained by connectivity and device access. This equity-oriented stance complements the pedagogy that as students rehearse high-leverage skills outside class, instructional time can be reallocated to conceptual discussion and problem framing, with greater confidence that basic fluencies will not bottleneck understanding (Dunlosky et al., 2013; Ryan & Deci, 2000; Sweller, 2011).

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