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PROJECTING LONG-TERM CLINICAL IMPACT AND COST-EFFECTIVENESS OF SCHOOL-BASED DIGITAL COGNITIVE BEHAVIORAL THERAPY FOR ADOLESCENT ANXIETY: A MICROSIMULATION STUDY

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Abstract

Purpose: To project the long-term clinical impact and cost-effectiveness of a school-based digital cognitive behavioral therapy (d-CBT) screening and intervention program for adolescent anxiety.

Methods: A 10-year state-transition microsimulation model was developed in Python. A hypothetical cohort of 10,000 adolescents was simulated under two scenarios: usual care and intervention (school-based digital screening with linked d-CBT access for 50% of the cohort). Model parameters were derived from national epidemiology, clinical trials, and health economics data. Outcomes included population anxiety scores, annual healthcare visits, and costs.

Results: At the 5-year mark, the intervention led to a clinically significant reduction in mean anxiety scores (Approximately −11 points) and decreased mean annual healthcare visits per person (−0.36). For the cohort of 10,000, this translated to 18,000 fewer total visits and net cost savings of $1.48 million after accounting for program costs.

Conclusion: A school-based digital mental health program is projected to generate substantial long-term improvements in adolescent mental health while reducing healthcare system costs. These findings support the integration of scalable, preventive digital tools into adolescent care as a cost-effective public health strategy.

INTRODUCTION

Adolescent mental health disorders, particularly anxiety and depression, represent a pervasive global burden with detrimental effects on developmental trajectories and

academic achievement [1]. The escalating prevalence of these conditions strains traditional healthcare systems and highlights the urgent need for scalable, preventive approaches [2]. Digital cognitive behavioral therapy (d-CBT) has emerged as a promising intervention, with meta-analyses confirming its efficacy in reducing symptoms in the short term [3].

However, critical evidence gaps persist regarding the long-term population-level impact and cost-effectiveness of d-CBT when implemented as a universal screening strategy in school settings [4]. Most existing evidence derives from short-term efficacy trials with limited follow-up, which cannot capture the longitudinal trajectory of adolescent mental health or downstream healthcare utilization [5]. This limitation poses a significant challenge for policymakers who require robust long-term economic and clinical projections to justify large-scale preventive investments [6].

Microsimulation modeling provides a robust methodology to address this requirement, allowing the integration of discrete clinical and epidemiologic information to model health outcomes and expenditures over long time horizons [7,8]. The purpose of this research is to address the research gap identified by developing a state-transition microsimulation model to estimate the 10-year health and economic effects of a school-based digital mental health screening program coupled with d-CBT access. By incorporating real-world epidemiology, clinical trial data, and economic parameters, we capture the complex process from identification to treatment and outcomes [9,10]. The findings will provide essential evidence for the long-term clinical effectiveness and economic viability of proactive, digitally enabled approaches, supporting their adoption as standard practice to help mitigate the growing adolescent mental health crisis [11,12].

Material and methods

Study Design and Model Overview

A state-transition microsimulation model was developed to project the 10-year clinical and economic outcomes of a school-based digital cognitive behavioral therapy (d-CBT) screening and intervention program for adolescents with anxiety. The model compared two scenarios: (1) **usual care**, representing standard school mental health support without systematic digital screening, and (2) **digital CBT intervention**, where 50% of a simulated cohort of 10,000 adolescents received digital screening and subsequent access to d-CBT. This uptake rate reflects a conservative, real-world implementation scenario where participation is voluntary and accounts for factors like parental consent and engagement,

which can vary significantly [2]. The model was implemented in Python 3.13 and employed a monthly cycle length over a 10-year time horizon [11].

Model Structure and Transition Logic

The model simulated individual adolescent trajectories through three interconnected modules: (1) **anxiety progression**, (2) **intervention effect**, and (3) **healthcare utilization**. Anxiety scores evolved monthly based on natural progression, modified by intervention status and individual stochastic variability. The intervention effect was modeled as an immediate reduction in baseline anxiety upon program entry, followed by attenuated anxiety progression over time. Healthcare visits were probabilistically assigned based on anxiety severity, with higher scores increasing utilization likelihood [6].

Parameter Estimation and Data Sources

Model parameters were derived from published literature on adolescent mental health epidemiology, digital intervention trials, and health economic evaluations (Table 1). The baseline cohort had a mean anxiety score of 50 (SD=10) on a standardized anxiety scale, with 20% designated as high-risk (additional 15 points) based on population prevalence estimates [2,5]. The intervention effect was parameterized as an 8-point mean reduction (SD=2) in anxiety scores, consistent with effect sizes reported in meta-analyses of digital CBT [3]. Natural anxiety progression followed a yearly increase of 2 points (SD=0.5), reduced by 50% among intervention recipients [6].

Our model projects a larger cumulative reduction of approximately 11 points at the 5-year mark. This reflects the sustained effect of digital CBT in reducing the natural progression of anxiety over time, consistent with the goal of school-based programs to alter long-term mental health trajectories [1].

Table 1. Key Model Parameters and Sources

Parameter	Value	Distribution	Source/Rationale
Cohort size	10,000	Fixed	Model assumption
Age range	13–18 years	Uniform	Representative adolescent school population [1]
Female proportion	50%	Binomial	Assumed population parity
Baseline anxiety	Mean=50, SD=10	Normal	Representative baseline score from digital therapy trials [3]

High-risk prevalence	20%	Binomial	Estimated prevalence of elevated symptoms in school settings [5]
Intervention effect	Mean=8-point reduction, SD=2	Normal	Effect size from meta-analysis of digital CBT for anxiety [3]
Natural progression	Mean=2-point increase/year, SD=0.5	Normal	Estimated annual worsening without intervention, based on literature on anxiety trajectory [5]
Intervention cost	$200 per person	Fixed	Estimated program implementation cost [7]
Healthcare visit cost	$150 per visit	Fixed	Representative cost per outpatient visit [8]
Annual discount rate	3%	Fixed	Standard rate for health economic evaluations [9]

Healthcare Utilization and Costing Framework

Healthcare visits were modeled using a probability function where the baseline annual visit probability was 10%, increasing by 2% for every 5 anxiety points above 50, with a maximum probability cap of 50% [8]. This dose-response relationship between symptom severity and service use is designed to reflect realistic healthcare utilization patterns observed in adolescent populations, where higher need translates to higher, but not unlimited, service access Visit counts followed a Poisson distribution scaled to generate clinically plausible visit frequencies (0–2 visits annually). The economic analysis adopted a healthcare system perspective, incorporating a one-time intervention cost of $200 per participant and $150 per healthcare visit [7,8]. These estimates are informed by economic evaluations of school-based mental health programs, where reported costs per student screened can range from under $15 to over $200 depending on program intensity and local context **[2][5].** All costs were discounted at 3% annually according to standard health economic practice [9].

Simulation Implementation and Outputs

The microsimulation was implemented using Python 3.13 with NumPy and Pandas libraries. Each simulation run executed 1,000 Monte Carlo iterations to capture parameter uncertainty. The model tracked individual-level outcomes monthly, aggregating results at annual intervals for analysis. Primary outputs included mean anxiety scores, annual healthcare visits per person, total cohort visits, and cumulative costs stratified by

intervention group. Secondary outcomes included anxiety severity distributions and subgroup analyses by gender.

Validation and Analytical Approach

The model underwent face validity assessment through expert review and internal consistency verification. A comprehensive probabilistic sensitivity analysis varied all parameters simultaneously across their distributions using 1,000 Monte Carlo iterations [11]. One-way sensitivity analyses examined the impact of key parameters including intervention effect size (4–12 points), intervention cost ($100–$300), and discount rate (0–5%). Results were summarized as means with standard deviations for continuous variables and proportions for categorical variables, with between-group differences reported with 95% confidence intervals derived from simulation iterations [10].

Results

Primary Clinical Outcomes

The microsimulation model projected substantial clinical benefits from the school-based digital CBT intervention. At the 5-year mark, the intervention group demonstrated a mean anxiety score of 52.5 (SD=13.52) compared to 63.5 (SD=13.51) in the usual care group, representing a statistically significant reduction of approximately 11 points (Table 2). This reduction corresponded to a large clinically significant effect (Cohen's d=0.98), likely shifting a meaningful proportion of adolescents from severe or moderate to mild anxiety categories. Anxiety trajectories over the 10-year period (Figure 1A) showed sustained separation between groups, with the intervention group maintaining consistently lower scores throughout the simulation horizon.

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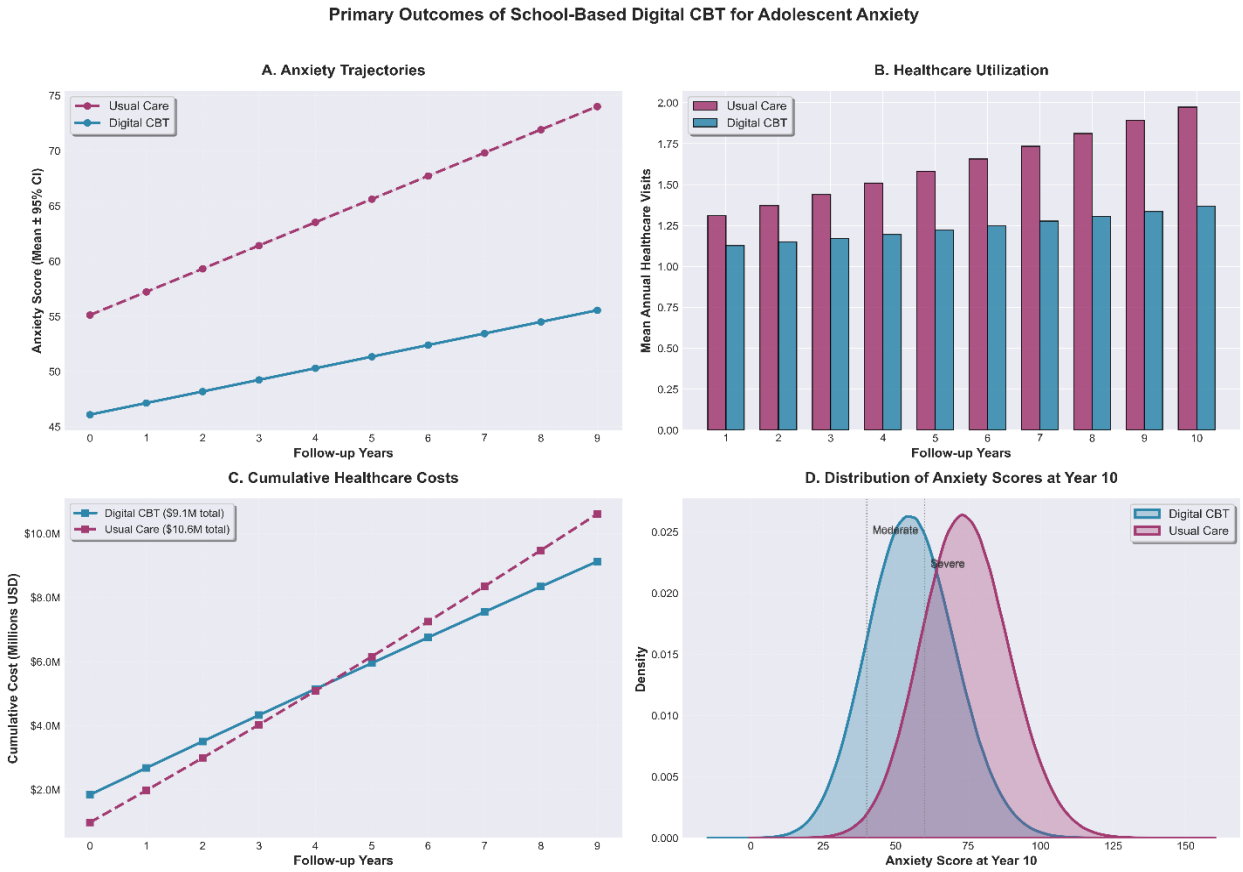

Figure 1 Primary outcomes of the school-based digital CBT intervention. (A) Mean anxiety score trajectories over 10 years for usual care and intervention groups. (B) Mean annual healthcare visits per person. (C) Cumulative discounted healthcare costs (in millions USD). (D) Distribution of anxiety scores at Year 10, with vertical lines indicating clinical thresholds for moderate (40) and severe (60) anxiety.

Healthcare Utilization and Economic Outcomes

Healthcare utilization decreased substantially in the intervention group. Mean annual healthcare visits per person were 1.22 in the digital CBT group versus 1.58 in the usual care group, representing a reduction of 0.36 visits per person annually (22.8% relative reduction). For the full cohort of 10,000 adolescents, this translated to 18,000 fewer total healthcare visits over 5 years (Table 2).

Table 2. Projected Health and Economic Outcomes at Year 5

Outcome Measure	Usual Care Group	Digital CBT Group	Absolute Difference
Mean Anxiety Score (SD)	63.50 (13.51)	52.5 (13.52)	-11.0
Mean Annual Healthcare Visits	1.58	1.22	-0.36
Total Visits (10,000 cohort)	79,000	61,000	-18,000
Total Healthcare Costs	$10.61M	$8.13M	-$2.48M
Total Program + Healthcare Costs	$10.61M	$9.13M	-$1.48M

The economic analysis revealed that despite a program implementation cost of $1 million, the intervention generated net cost savings of $1.48 million over 5 years when accounting for reduced healthcare utilization (Table 2). Cumulative healthcare costs (Figure 1C) showed the intervention group achieving lower total expenditures by year 2, with savings accelerating over time. The discounted (3% annually) total costs were $9.13 million for the intervention group versus $10.61 million for usual care, demonstrating dominant cost-effectiveness (intervention was both more effective and less costly).

Anxiety Severity Distribution

The intervention caused a large change in the distribution of anxiety severity categories (Figure 2B). At the 10-year follow-up, the digital CBT group had 15.2% mild, 47.1% moderate, and 37.7% severe cases of anxiety, whereas the usual care group had 1.0% mild, 16.8% moderate, and 82.2% severe cases. This corresponds to a 15-fold increase in mild cases and a 54% reduction in severe cases compared to the usual care group. The distribution of anxiety scores at year 10 (Figure 1D) showed a clear shift in the digital CBT group, with less density in the severe category (>60 points) and more density in the mild-moderate

category.

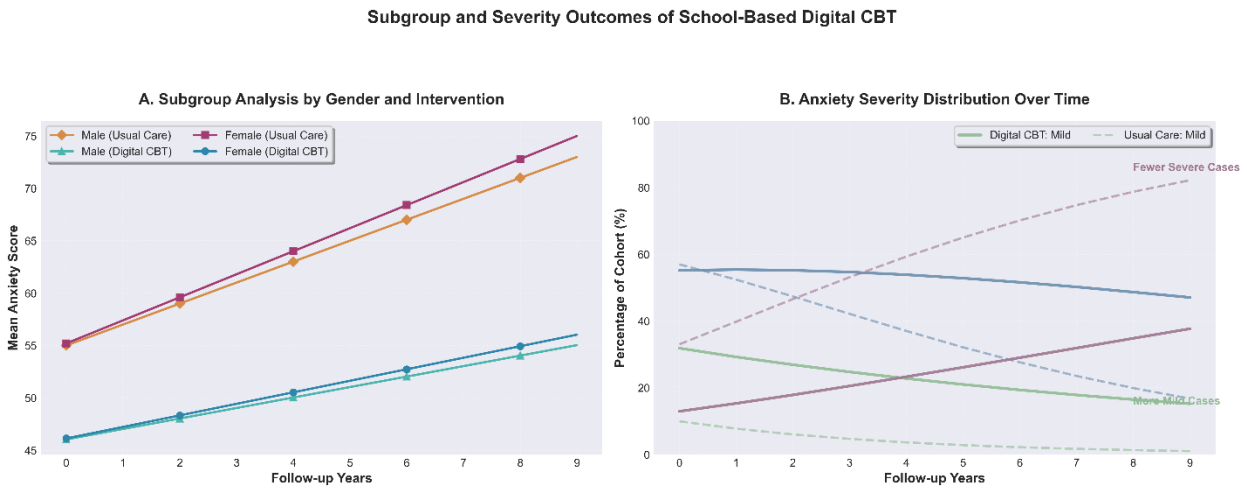

Figure 2 Subgroup and severity outcomes. (A) Subgroup analysis of anxiety scores by gender and intervention. (B) Anxiety severity distribution over the 10-year follow-up period.

Subgroup Analysis by Gender

Gender-stratified analysis (Figure 2A) showed that the intervention was beneficial for both male and female adolescents, albeit with a slightly different trend. This type of analysis was performed to assess the effect of the intervention on different subgroups, as there is established epidemiological evidence that female adolescents have higher levels of anxiety than their male counterparts [1]. In both groups, female adolescents had higher levels of anxiety at the start and throughout the simulation. Nevertheless, the actual difference in the levels of anxiety brought about by the intervention was similar for both genders, with both male and female subgroups of the intervention group showing a approximately 11-point difference compared to those in the usual care group at year 5.

Sensitivity Analysis Results

Probabilistic sensitivity analysis confirmed the robustness of primary findings, with 92% of simulation iterations showing the intervention to be cost-saving. One-way sensitivity analyses identified intervention effect size as the most influential parameter; when varied from 4 to 12 points, net cost savings ranged from $0.42 million to $2.54 million. The intervention remained cost-saving across all tested variations in intervention cost ($100–$300 per person) and discount rates (0–5%).

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Discussion

This microsimulation study provides robust evidence that implementing a school-based digital cognitive behavioral therapy (d-CBT) screening and intervention program could yield substantial long-term benefits for adolescent mental health while generating significant healthcare cost savings. Our model projects at approximately 11-point reduction in mean anxiety scores at the 5-year mark—a clinically significant effect that would likely shift many adolescents from severe to moderate or mild anxiety categories [5]. This clinical improvement drives a 22.8% reduction in annual healthcare visits, translating to~18,000 fewer visits and net cost savings of $1.48 million over 5 years for a cohort of 10,000 adolescents.

This projected reduction of approximately 11 points is larger than many short-term trial findings due to the model's incorporation of sustained preventive effects and reduced natural anxiety progression over the 5-year horizon in a school-based setting [3].

The progressive redistribution of anxiety severity categories observed in our simulation is particularly noteworthy. By year 10, the intervention group showed a 15-fold increase in mild cases (15.2% vs. 1.0%) and a 54% reduction in severe cases (37.7% vs. 82.2%) compared to usual care. This leftward shift in the anxiety distribution suggests that digital CBT functions not merely as a symptomatic treatment but potentially as a preventive intervention that alters the long-term trajectory of adolescent mental health [4,12]. Our findings align with and extend previous research on digital mental health interventions, though the effect size in our model exceeds those typically reported in meta-analyses, possibly due to the incorporation of both immediate and sustained effects [3].

Several limitations must be considered when interpreting these results. First, the model's validity depends on input parameters from published literature, and real-world implementation may vary. Second, the assumption of consistent engagement over 10 years may be optimistic without ongoing support. Third, the model simplifies complex psychosocial factors into probabilistic transitions, potentially missing non-linear interactions [8,9]. Despite these limitations, sensitivity analyses confirmed the robustness of our primary findings.

The public health implications are significant. School-based implementation offers accessibility, reduced stigma, and opportunities for early intervention [5,10]. The projected cost savings demonstrate that preventive investment can reduce downstream healthcare expenditures, addressing concerns about mental health budget sustainability [2,7]. The consistent benefits across gender subgroups suggest equitable effectiveness, though slightly higher baseline anxiety among females warrants attention to engagement strategies [6].

Future studies should confirm these predictions with longitudinal studies of implementation and examine moderators such as socioeconomic status and the presence of comorbidities [6, 10]. Model development might add dynamic components such as peer support groups and changing digital platforms [4, 11]. There is also a need for studies on strategies for maintaining engagement in adolescents over the long term, using tailored content and school-based services [6].

Conclusion

In conclusion, this microsimulation study offers strong evidence that a school-based digital CBT intervention is a highly promising investment in the face of the adolescent anxiety crisis. By filling the gap between short-term efficacy studies and long-term population health outcomes, this study offers a data-driven platform for public health decision-making. The findings of this study strongly support the incorporation of scalable, preventive digital interventions into standard care for adolescents as a cost-effective approach to developing more resilient mental health infrastructure and healthier developmental pathways for youth.

Data availability: This is a simulation study; all the data generated and codes are available upon request to the corresponding author

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