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Meta-Mar: An AI-Integrated Web Platform for Meta-Analysis

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Summary

Meta-analysis is a cornerstone methodology in evidence-based research, enabling systematic synthesis of findings across multiple studies to produce more reliable and generalizable conclusions (Borenstein et al., 2021; Gurevitch et al., 2018). Yet despite its central importance, existing tools for conducting meta-analyses remain fragmented—often technically demanding, costly, or lacking transparency—creating barriers for early-career researchers, educators, and interdisciplinary teams (Harrer et al., 2021).

Meta-Mar addresses this challenge as a free, browser-based meta-analysis platform that combines statistical rigor with accessibility. Built with R Shiny and powered by the `metafor` (Viechtbauer, 2010) and `meta` (Balduzzi et al., 2019) packages, Meta-Mar v4.0.2 performs fixed-effect and random-effects meta-analyses across continuous, binary, correlation, and generic inverse-variance data structures. The platform integrates advanced heterogeneity diagnostics, publication bias assessments, and publication-quality visualizations within a guided, stepwise interface. Uniquely, Meta-Mar incorporates a large language model (LLM) assistant via GPT-4 that provides contextual guidance for model selection, data validation, and result interpretation—bridging the gap between statistical complexity and practical usability.

Available at https://www.meta-mar.com, Meta-Mar has been used by over 5,800 researchers across 120+ countries and cited in 200+ peer-reviewed publications since its initial release in 2020 (Beheshti et al., 2020).

Statement of Need

The current landscape of meta-analysis software presents a fundamental tension between methodological sophistication and day-to-day usability (Fisher et al., 2022; Harrer et al., 2021). Commercial platforms such as Comprehensive Meta-Analysis (CMA) and Cochrane's RevMan offer comprehensive functionality but operate under subscription-based models (approximately €65–95 annually for students), creating financial barriers particularly for researchers in resource-limited settings. Open-source alternatives like the R packages `metafor` and `meta` provide robust analytical frameworks but require programming expertise that many researchers—especially those in applied fields such as health, education, and behavioral sciences—may lack.

Existing web-based tools have attempted to bridge this gap, but typically sacrifice either statistical comprehensiveness or methodological guidance. Platforms like metaHUN (Umaroglu & Ozdemir, 2018) provide web-based access to `metafor` functionality but lack features such as customizable pooling methods, prediction intervals, and interactive tutorials. Desktop applications like JASP (Bartoš et al., 2025) require installation, which can pose barriers in institutional computing environments.

Meta-Mar addresses these limitations by providing:

- **Zero-barrier accessibility:** Browser-based interface requiring no installation, registration, or payment
- **Comprehensive statistical coverage:** Support for continuous, binary, and correlation outcomes with multiple effect size measures (SMD, MD, OR, RR, RD, Fisher's z)
- **Methodological flexibility:** Eight heterogeneity variance estimators (REML, DL, PM, ML, EB, SJ, HE, HS) with small-sample corrections (Hartung-Knapp, Kenward-Roger)
- **Publication bias diagnostics:** Funnel plots, Egger's regression (Egger et al., 1997), Begg's rank correlation, trim-and-fill adjustment (Duval & Tweedie, 2000), and fail-safe N calculations (Rosenthal, Orwin, Rosenberg)
- **AI-powered guidance:** Context-aware interpretation and methodological recommendations that serve as a dynamic tutor for users unfamiliar with meta-analytic conventions
- **Privacy-by-design:** GDPR-aligned data handling with no persistent storage; all uploads deleted after session ends

Statistical Architecture

Meta-Mar implements the complete meta-analysis workflow through a modular architecture:

Data Input and Effect Size Calculation. The platform accepts CSV uploads or manual entry for four data structures: continuous outcomes (computing SMD, MD, or ratio of means), binary outcomes (OR, RR, RD with zero-event handling), correlations (Fisher's z transformation), and pre-calculated effect sizes (generic inverse variance). Input validation ensures data integrity before analysis.

Model Specification. Users select between fixed-effect models using inverse-variance weighting and random-effects models with user-specified τ^2 estimators. Confidence interval methods include classic Wald intervals, Hartung-Knapp-Sidik-Jonkman (HKSJ), and Kenward-Roger corrections for improved small-sample performance.

Heterogeneity Assessment. The platform computes Cochran's Q statistic, I^2, τ^2, H^2, and prediction intervals (Higgins et al., 2003), enabling researchers to distinguish between true between-study heterogeneity and sampling variation.

Publication Bias Analysis. Visual assessment via funnel plots (including contour-enhanced variants) is complemented by Egger's regression test for small-study effects, Begg's rank correlation, trim-and-fill adjustment for estimating missing studies, and three fail-safe N methods for quantifying robustness.

Moderator Analysis. Subgroup analysis supports categorical moderators with between-group heterogeneity testing, while meta-regression accommodates continuous and categorical covariates with bubble plot visualization.

Visualization. Publication-quality outputs include forest plots (with subgroup comparisons), funnel plots, Galbraith (radial) plots, L'Abbé plots for binary outcomes, Baujat plots for identifying influential studies, and drapery plots for p-value functions.

Validation. Computational accuracy was validated against Cochrane RevMan 5.4, demonstrating agreement to four decimal places for effect size estimates, standard errors, confidence intervals, and study weights across standardized mean difference models.

State of the Field

Meta-analysis software spans commercial, open-source, and web-based solutions, each with distinct trade-offs. Commercial platforms like Comprehensive Meta-Analysis (CMA) and Cochrane's RevMan provide comprehensive functionality but require paid licenses

(€65–95/year for students), limiting access in resource-constrained settings. Open-source R packages—particularly `metafor` (Viechtbauer, 2010) and `meta` (Balduzzi et al., 2019)—offer robust analytical frameworks but demand programming expertise. Desktop applications like JASP (Bartoš et al., 2025) require local installation, which can be problematic in institutional environments with restricted software policies. Web-based alternatives such as metaHUN (Umaroglu & Ozdemir, 2018) provide browser access but lack customizable pooling methods, prediction intervals, and methodological guidance. No existing tool combines zero-barrier web accessibility, comprehensive statistical methods, and AI-powered interpretive support within a single platform.

Software Design

The architectural decisions underlying Meta-Mar reflect deliberate trade-offs between statistical power, accessibility, and maintainability:

Build vs. contribute decision. Rather than implementing meta-analytic algorithms from scratch or contributing directly to existing packages, Meta-Mar wraps the established `metafor` and `meta` R packages through an accessibility layer. This choice prioritizes computational reliability over novelty—these packages have been peer-reviewed, widely cited, and validated across thousands of published meta-analyses. Contributing directly to these packages would not address the core accessibility gap: users without R programming skills cannot benefit from command-line tools regardless of their statistical sophistication. Our contribution lies in the web interface and AI integration layer, not in reinventing statistical methods.

Web-based vs. desktop architecture. We chose R Shiny over desktop deployment to eliminate installation barriers. This enables immediate use in institutional environments with restricted software policies and supports the platform's educational mission in classroom settings where setup time is limited.

AI as guidance, not automation. The GPT-4 integration was designed as an interpretive assistant rather than an automated analyst. Statistical computations remain deterministic and reproducible through the underlying R packages; the AI layer provides explanatory support without modifying analytical outputs. This separation ensures that research conclusions depend on validated statistical methods, not on LLM outputs.

Privacy-first data handling. Session-based data storage with automatic deletion was chosen over persistent user accounts to minimize data governance complexity and align with GDPR principles. This trade-off sacrifices cross-session continuity for stronger privacy guarantees.

AI Integration

Meta-Mar integrates OpenAI's GPT-4 API through LangChain to provide an optional AI assistant that enhances interpretability without modifying statistical computations. The assistant supports users with:

- Contextual interpretation of effect sizes, confidence intervals, and heterogeneity statistics
- Guidance on model selection based on data characteristics and research questions
- Explanation of publication bias diagnostics and their implications
- Interactive methodological tutoring for users new to meta-analysis

The integration employs conversation memory to maintain context across multi-turn interactions, custom prompt templates tailored to meta-analytic workflows, and error handling for invalid inputs or API timeouts. Critically, the AI assistant is designed to support—not replace—researcher judgment. All AI outputs are clearly labeled, statistical computations remain deterministic and reproducible, and users retain full control over analytical decisions.

AI Usage Disclosure

The AI assistant within Meta-Mar is an optional feature that users may enable or disable. During platform development, AI coding assistants were used as follows:

- **Tools used:** GitHub Copilot, Claude 3.5 Sonnet (Anthropic)
- **Scope of assistance:** Code refactoring, UI component scaffolding, documentation drafting, and test case generation
- **Where applied:** Shiny UI modules, API integration code, README and documentation text
- **Human oversight:** All AI-generated outputs were reviewed, edited, and validated by the authors. Core design decisions, statistical implementations, and architectural choices were made entirely by human authors.

Core statistical computations rely entirely on the peer-reviewed `metafor` and `meta` R packages without AI modification. The AI assistant feature uses the OpenAI GPT-4 API; this integration was designed and implemented by the authors with AI coding assistance for boilerplate code only. This paper was drafted by the authors with AI assistance for grammar and structure review.

Privacy and Governance

Meta-Mar implements privacy-by-design principles aligned with GDPR requirements:

- No user registration required
- Uploaded data stored in session memory only
- Automatic deletion when session ends
- Automated anonymization of free-text inputs before AI processing
- TLS 1.3 encryption for all data transmission
- No persistent storage of user data or AI interactions

These safeguards ensure responsible deployment in academic and educational environments where data sensitivity is paramount.

Development Practices and Community

Meta-Mar has been in continuous development since 2019, with the current architecture (v4.0) representing a complete rewrite initiated in March 2025. Earlier versions were developed outside public version control; Meta-Mar's prior existence is documented in peer-reviewed literature, including Beheshti et al. (2020) which references Meta-Mar v1.1.0. The repository includes:

- **Documentation:** Comprehensive README, online user guide at meta-mar.com/documentation, and in-app tooltips
- **Issue tracking:** Public issue tracker for bug reports and feature requests
- **Contribution pathway:** Guidelines for community contributions via pull requests
- **Versioned releases:** Tagged releases with semantic versioning (current: v4.0.2)
- **Validation testing:** Computational outputs verified against Cochrane RevMan 5.4 benchmark data

The platform can be tested locally by cloning the repository and running `shiny::runApp()` in R with the required dependencies installed.

Research Impact Statement

Meta-Mar demonstrates realized research impact through multiple indicators:

- **User adoption:** Over 5,800 researchers across 120+ countries have used the platform since its 2020 launch
- **Citation evidence:** 200+ peer-reviewed publications have cited Meta-Mar as their meta-analysis tool
- **Educational integration:** Adopted in graduate-level meta-analysis courses, including PhD programs at Semmelweis University (Budapest), demonstrating utility as both a research and pedagogical tool
- **Computational validation:** Results verified against Cochrane RevMan 5.4 to four decimal places for effect estimates, standard errors, and confidence intervals

Meta-Mar serves two complementary user groups: (1) researchers without programming expertise who require accessible tools for conducting methodologically sound meta-analyses, and (2) technically trained users who may lack formal training in meta-analytic methodology and benefit from AI-driven guidance on model selection and interpretation.

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