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hdmax2, an R package to perform high dimension mediation analysis

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Abstract

Mediation analysis plays a crucial role in epidemiology, unraveling the intricate pathways through which exposures exert influence on health outcomes. Recent advances in high-throughput sequencing techniques have generated growing interest in applying mediation analysis to explore the causal relationships between patient environmental exposures, molecular features (such as omics data) and various health outcomes. Mediation analysis handling high-dimensional mediators raise a number of statistical challenges. Despite the emergence of numerous methods designed to tackle these challenges, the majority are limited to continuous outcomes. Furthermore, these advanced statistical approaches have yet to find widespread adoption among epidemiologists and health data scientists in their day-to-day practices. To address this gap, we introduce an R package specifically tailored for high-dimensional mediation analysis using the max-squared method (HDMAX2). This tool aims to mitigate these obstacles by providing a practical solution for researchers and practitioners eager to explore intricate causal relationships in health data involving complex molecular features. Here we improve the HDMAX2 method, and expand its capabilities to accommodate multiple exposures and non-continuous variables. This improvement enables its application to a diverse array of mediation analysis scenarios, mirroring the complexity often encountered in healthcare data. To enhance accessibility for users with varying expertise, we release an R package called `hdmax2`. This package allows users to estimate the indirect effects of mediators, calculate the overall indirect effect of mediators, and facilitates the execution of high-dimensional mediation analysis.

Keywords: High-dimension; Mediation; Multivariate analysis; Confounding effect; Causal analysis

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Introduction

2

3 When a statistical association is observed between an external exposure (X) and an individ-
4 ual outcome (Y), one or more intermediate variables (M) (such as gene expression or epigenetic
5 changes) may mediate this effect. Identifying and assessing the mediating role of these variables
6 in the effect of X on Y is crucial for deciphering underlying causal mechanisms in epidemiologi-
7 cal and clinical research. This process, known as mediation analysis, involves studying mediator
8 variables to define the causal structure between X and Y . The mediated effect, termed the indi-
9 rect effect, is equal to the effect of X on Y mediated through M , to distinguish from the direct
10 effect of X on Y unexplained by M (Richiardi et al., 2013). Historically, mediation analysis has
11 predominantly focused on single mediation (i.e. one intermediary variable) (Baron and Kenny,
12 1986), running separate statistical tests for the effects of X on M and M on Y , followed by
13 estimation of the indirect effect (Imai et al., 2010; Sobel, 1982). However, in the realm of high-
14 dimensional molecular data (M , e.g., omic data), extending mediation analysis to high dimensions
15 poses challenges, including correction for multiple testing, controlling the false discovery rate
16 (FDR), addressing reverse causation, adjusting for confounding effects, considering interactions
17 among mediators, and integrating multimodal data types (Blum et al., 2020; Zeng et al., 2021).
18 Currently, there remains no consensus on the optimal combination of models and methodologies
19 for high-dimensional mediation analysis. With the increasingly prevalent use of next-generation
20 sequencing technologies, there is now an urgent need to develop high-performing methods in
21 high dimensionality and make them accessible. While recent methods has partially addressed
22 these needs (Dai et al., 2022; Djordjilović et al., 2022; Sampson et al., 2018; Zhang et al., 2016),
23 particularly in controlling the type I error in high dimension, they do not account for unmeasured
24 confounding factors and do not allow for the consideration of multiple exposures.

25 In this article, we introduce an R package called `hdmax2`. The HDMAX2 method was origi-
26 nally proposed by Jumentier et al., 2023. The fundamental concept behind HDMAX2 methods
27 is to use a latent factor mixed regression model for estimating unobserved latent factors while
28 conducting high-dimensional association analysis. HDMAX2 also implements a novel procedure
29 known as the max-squared test to assess the statistical significance of potential mediators (see
30 Materials and Methods section). Finally, HDMAX2 enables the calculation of an overall indirect
31 effect from a single model that includes all mediators simultaneously. This approach therefore
32 takes into account correlations between mediators. A case study investigating the impact of
33 maternal smoking on birth weight identified epigenetic regions mediating the indirect effect
34 of this exposure (Jumentier et al., 2023). In this article, we introduce an enhanced version of
35 the HDMAX2 method, expanding its functionalities and making the method accessible to prac-
36 titioners through a packaged format. The `hdmax2` program has been enriched with numerous
37 features, including the ability to manage various types of variables in the exposure (continuous,
38 binary, categorical, and multivariate), as well as the capability to incorporate binary outcomes.
39 This package enables users to (i) investigate associations between the variables X , M , and Y , (ii)
40 compute the mediated effect for each potential mediator, (iii) assess the overall indirect effect for
41 the total model, and (iv) visualize these results. A graphical model of the package is presented in
42 Fig 1. The package is open-source and accessible on our GitHub page at <https://github.com/bcm-uga/hdmax2>.
43

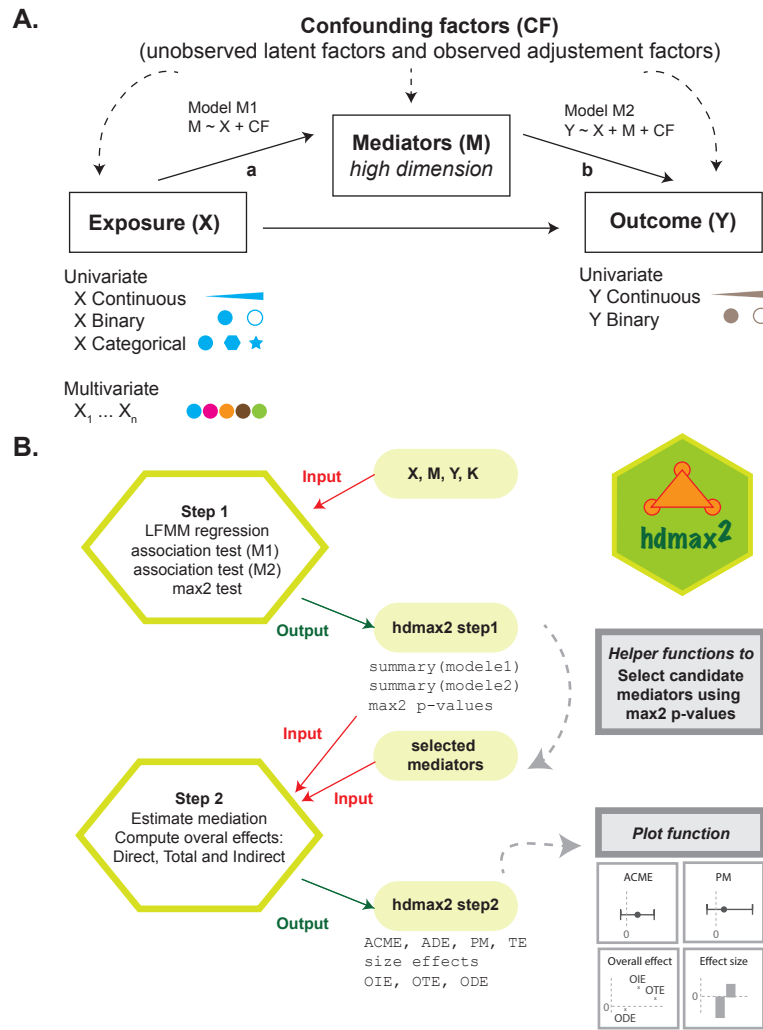


Figure 1 – Graphical model of the hdmx2 R package. **A.** Acyclic graph of HDMAX2 method for conducting high-dimension mediation analysis. Exposure variables (X) can be univariate or multivariate, the colors represent different types of variable, and the symbols schematically represent the modalities of the same variable. Intermediary variables (M) are continuous variables. The outcome variable (Y) can be binary or continuous. Confounding factors represent observed adjustment factors and unobserved latent factors estimated by LFMM regression. The values a and b represent the effect sizes for each regression of the mediation model. **B.** Core structure of the hdmx2 package. Step 1: First, latent factors are estimated by LFMM multivariate regression. Then, the association of X and M and of M and Y are statistically tested in simple regression models and the significance values obtained are combined, for each potential mediator. Step 2: the indirect effects of the mediator variables are estimated, along with various causal measures of interest: ACME (Average Causal Mediated Effect), ADE (Average Direct Effect), PM (Proportion Mediated), TE (Total Effect), size effects, OIE (Overall Indirect Effect), OTE (Overall Total Effect), ODE (Overall Direct Effect).

44

Materials and methods

45 The package comprises a set of core functions along with a visualization function. Its usage
 46 is guided through several vignettes and test datasets. The statistical methodologies embedded
 47 within the package are described below, with the initial application case documented by Jumen-
 48 tier et al., 2023.

49 **Input data.** The `hdmax2` package is designed to accept one or several exposure variables, X ,
 50 which can be continuous, binary, or categorical. The user must provide an exposure `data.frame`
 51 having at least one column as input. We define N as the number of samples within the tested
 52 cohort. Therefore, each exposure and outcome variable consists of N measurements. In the R
 53 language, categorical variables are encoded as factor objects. The function `as.factor()` can
 54 be used to encode categorical variables. The functions `levels()` and `ordered()` can be used
 55 to define the order of the modalities of categorical variables. By convention, `hdmax2` uses the
 56 first modality as a reference to calculate the effects associated with the other modalities of the
 57 variable, as encoded by default in `lm()` function in R. Continuous intermediary variables, de-
 58 noted as M , are represented as a matrix encompassing potential mediators, such as methylome
 59 or transcriptome molecular features. The matrix M should be entered as a separated input,
 60 without missing values. The intermediary variable matrix M is of dimension $J \times N$, with J the
 61 total number of intermediate variables. The outcome variable, denoted as Y , corresponds to a
 62 vector of dimension N , which supports both continuous and binary formats. Continuous and
 63 binary variables must be encoded in numeric format. Optional covariates, Z , can be included as
 64 observed adjustment factors in the model. The package `hdmax2` also takes as input the number
 65 of latent factors to be estimated, K .

66

67 **Step 1: Identification of potential mediators.** The function `hdmax2::run_AS()` evaluates the as-
 68 sociation between exposure variables, intermediary variables and the outcome variable using a
 69 latent factor mixed model (LFMM (Caye et al., 2019)) to estimate K unobserved latent factors U .
 70 First this function tests the significance of association between the exposure variables and a the
 71 potential mediator variables. Then it tests association between the potential mediator variables
 72 and the outcome variable. Finally it evaluates the significance of the indirect effects.

73 For univariate (continuous, binary and categorical) exposure, a significance value $P_{1,j}$ is com-
 74 puted by the `hdmax2` program for the test of a null effect size for exposure variable X on inter-
 75 mediary variable M_j , for each j (with j ranging from 1 to J , the total number of intermediary
 76 variables). For multivariate exposure, the `hdmax2` program applies partial regression models, and
 77 returns a single P -value, $P_{1,j}$, for the test of a null effect size of the full exposure variable X on
 78 the intermediary variable M_j , for each j (see Fig 1.A, regression 1). Then, the `hdmax2` program
 79 returns a significance value $P_{2,j}$ corresponding to the association of each intermediary variable
 80 M_j with the outcome variable Y (see Fig 1.A, regression 2).

81 Finally `hdmax2` identifies potential mediators by combining the significance values P_1 and P_2
 82 to compute a P -value for each intermediary variable using the max-squared (\max^2) test (equation
 83 (1)). This test rejects the null hypothesis of no effect of exposure on potential mediators or no
 84 effect of potential mediators on the outcome.

$$(1) \quad P = \max(P_1, P_2)^2.$$

85 The `hdmax2::run_AS()` function returns an object of class `hdmax2_step1`, including the fol-
 86 lowing attributes:

- 87 - a vector of J mediation P -values, resulting of the max-squared test,
- 88 - U , score matrix of size $N \times K$, corresponding to the K unobserved latent factors calculated
- 89 from an LFMM regression (model M1),

90 - the input variables of the model: exposure variables X , the outcome variable Y , and adjust-
91 ment factors Z (when applicable).

92 **Step 2: Estimation of indirect effects.** The function `hdmax2::estimate_effect()` takes as in-
93 put an object `hdmax2_step1` and a list of potential mediators M^S to be analyzed in subsequent
94 steps. The subset M^S is defined by the user based on the output of `hdmax2_step1`. We provide
95 a series of helper functions to guide the user in the selection of M^S . These functions include a
96 False Discovery Rate (FDR) control approach, or the possibility to aggregate mediator regions
97 according to their location on the genome. Aggregating mediator regions allows, for instance,
98 the inference of differentially methylated regions (DMRs) when working with DNA methylation
99 data. Illustrations of these approaches can be found in Jumentier et al., 2023 and in the `hdmax2`
100 vignettes.

101 For each univariate exposure variable and the subset of mediators M^S , the
102 `hdmax2::estimate_effect()` function computes several estimates to evaluate the indi-
103 rect effects in the path between exposure variables and the outcome variable. Initially, this
104 function assesses each mediator variable M_j^S individually and computes causal measures of
105 interest such as (i) the Average Causal Mediated Effect (ACME, corresponding to the indirect
106 effect) and (ii) the Proportion Mediated (PM). The ACME differs from the Average Direct Effect
107 (ADE), which represents the unmediated effect, and from the Total Effect (TE) which is equal
108 to the sum of direct and indirect effect. PM corresponds to the proportion of the total effect
109 that is mediated by the mediator (ratio of the indirect effect to the total effect). ACME and
110 PM are computed by the `mediation::mediate()` function of the package `mediation`, that
111 automatically detects the type of statistical model used in the mediation analysis (Tingley
112 et al., 2014). The function `mediation::mediate()` calculates uncertainty estimates by a
113 quasi-Bayesian Monte Carlo approach described in (Imai et al., 2010). In addition, it estimates
114 the intermediary effect sizes a_j and b_j and their standard deviations (see Fig 1A). Eventually,
115 `hdmax2` calculates an Overall Indirect Effect (OIE) from a single model that includes all mediators
116 M^S simultaneously. The OIE corresponds to the sum of the indirect effect associated with
117 all mediators. The confidence interval (CI) of the OIE is estimated by a bootstrap approach.
118 Along with the OIE, `hdmax2` estimates the Overall Total Effect (OTE) corresponding to the
119 effect of exposure variables on the outcome variable, as well as the Overall Direct Effect (ODE)
120 corresponding to the effect of exposure variables on the outcome variable when the mediators
121 M^S are included in the model. For categorical variables, all estimates (ACME, TE, OIE, OTE,
122 ODE and size effects) are calculated relative to a reference corresponding to the first modality
123 of the variable. In the case of a multivariate exposure, each variable is treated independently,
124 the other variables being included in the covariable matrix of the mediation model.

125 The `hdmax2::estimate_effect()` function returns an object of class `hdmax2_step2`, includ-
126 ing the following attributes:

- 127 - ACME (average causal mediated effect), ADE (average direct effect), PM (proportion medi-
128 ated) and TE (total effect), for each mediator,
- 129 - OIE (overall indirect effect), OTE (overall total effect) and ODE (overall direct effect),
- 130 - summaries of regression models adjusted during the mediation analysis.

131 The function `hdmax2::plot()` takes as input an object `hdmax2_step2` and enables graphical
132 visualization of mediated effects. This function returns an ACME forest plot, a PM forest plot, a
133 plot of the overall effects and a plot of the indirect effect sizes a and b .

134 **Data collection and preprocessing.** The breast cancer dataset was collected from the TCGA-
135 BRCA public repository. DNA methylation data underwent filtering to remove probes contain-
136 ing NA values, resulting in the retention of approximately 20,000 CpG sites. Gene expressions
137 were normalized using standard DESeq2 parameters (Love et al., 2014) and pseudo-log trans-
138 formed. The multiple sclerosis dataset was collected from the GEO public repository (accession
139 number : GSE137143 (Kim et al., 2021)). RNA-seq data underwent normalization using stan-
140 dard DESeq2 parameters (Love et al., 2014) and were filtered to retain only coding genes with
141 detectable expression (>0 in at least one sample). Filtered data were subsequently transformed
142 using pseudo-logarithmic transformation.

143 **Bioinformatic analysis.** Gene set enrichment analysis were performed using the `fgsea` (Korotke-
144 vich et al., 2021) and `msigdb` (Dolgalev, 2022) R packages, using the defaults parameters. Gene
145 ranks correspond to $-\log_{10}(\text{max-squared pvalues})$.

146

Results

147 **Description of the package vignette.** We propose several vignettes to explain the use of the
148 package based on simulated data: an analysis case with a univariate exposure, an analysis case
149 with a multivariate exposure and a vignette to illustrate the usage of helper functions.

150 **First use case : HER2 and breast cancer.** In this example study, we employed mediation analysis
151 to assess the potential causal role of DNA methylation in the pathway linking HER2 status of
152 Breast Cancer to a survival prognostic factor, namely the risk score. Our investigation utilized
153 data from the TCGA-BRCA repository. The risk score was derived from a six-gene expression
154 signature, as described by (Yin et al., 2024), and is inversely correlated with patient survival.
155 HER2 positive status contributes to the molecular subtyping of breast cancer, which includes
156 'estrogen and progesterone receptor-positive, HER2 negative' (Luminal A), 'hormone positive
157 and HER2 negative' (Luminal B), as well as 'HER2 positive' and 'triple-negative breast cancer
158 (TNBC)' subtypes (Orrantia-Borunda et al., 2022). The computation of the risk score was based
159 on RNAseq data, following the methodology outlined by (Yin et al., 2024). We categorized
160 patients based on HER2 status, dividing them into HER2-positive ($n=176$) and HER2-negative
161 ($n=752$) groups, while filtering out equivocal ($n=22$) and indeterminate ($n=8$) cases. Our analyti-
162 cal model included X as a binary exposure variable representing HER2 expression ($0 = \text{negative}$,
163 $1 = \text{positive}$), M encompassing 20,000 methylation probes, and Y denoting the continuous risk
164 score.

165

166 In our analysis, after adjusting for the confounding effect of age, we found that the total ef-
167 fect of HER2-positive status resulted in a 0.30 higher risk score (t-test, $p=0.007$, $sd = 0.11$). For
168 the initial step of the HDMAX2 approach, we opted to use $K = 2$ latent factors in the association
169 study. Subsequently, we identified the top 10 potential mediators with the lowest max-squared
170 P -values. We then estimated the individual indirect effect of each mediator by computing the Av-
171 erage Causal Mediation Effect (ACME) as depicted in Fig 2A, along with the proportion mediated
172 shown in Fig 2B. Following this, we calculated the Overall Indirect Effect and its corresponding
173 Overall Direct Effect, as illustrated in Fig 2C. In our analysis, we observed a negative direct effect
174 of HER2 on the risk score, suggesting that HER2 expression in breast tumors has a protective ef-
175 fect on survival. However, the indirect effect mediated by the top 10 CpG probes corresponded
176 to a 0.61 increase in the risk score (standard deviation = 0.07). This indicates that the mediated

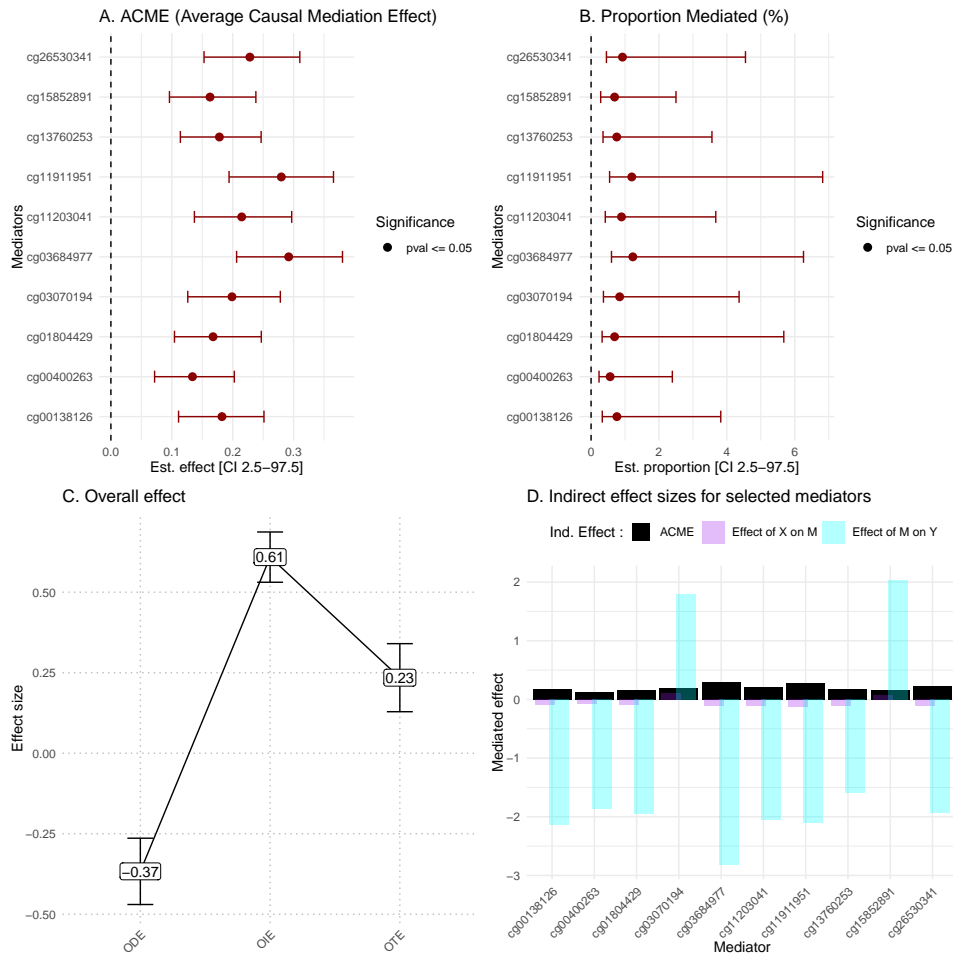


Figure 2 – Summary of the breast cancer use case. A. Estimates of indirect effect (ACME) and **B.** proportions of mediated effect (PM) for the top 10 mediators. The effect estimate is represented by a dot and its 95% CI by the bar. Symbols correspond to the significance cut off of 5% (square for P -value ≥ 0.05 , circle P -value < 0.05). Colors correspond to the sign of the effect (green for estimated effect ≤ 0 , red for estimated effect > 0). **C.** Effect sizes of Overall Direct Effect (ODE), Overall Indirect Effect (OIE) and Overall Total Effect (OTE). Error bars correspond to standard deviation (ODE and OTE) or confidence interval (OIE). **D.** Indirect effect sizes for the selected mediators. Black corresponds to the ACME, violet to the effect of exposure X on mediator M in the model $X \sim M$, and blue corresponds to the effect of mediator M on outcome Y in the model $Y \sim M + X$.

177 effect is detrimental to patient survival, resulting in the observed total effect of 0.30 on the risk
 178 score. Interestingly, in our analysis, we noted that for 8 out of the 10 identified mediators, the
 179 positive Average Causal Mediation Effect (ACME) resulted from a double negative effect: firstly,
 180 from HER2 status (X) to methylation (M), and secondly, from methylation (M) to risk score (Y)
 181 (Fig 2D). This observation suggests a complex interplay between the exposure, mediators, and
 182 outcome, where the presence of the mediator counterbalance the negative effect of the expo-
 183 sure on the outcome. This phenomenon highlights the complex relationships within biological
 184 pathways involved in tumor growth and patient survival. This result highlights the importance
 185 of considering mediators to understand the mechanisms underlying seemingly simple observed
 186 associations. Remarkably, most of the top 10 identified mediators were associated with genes
 187 known to be involved in breast cancer biology, thus supporting the biological relevance of our
 188 approach (see Table 1).

ID	Chromosome	Start	Gene Symbol	Pubmed hits
cg11911951	chr16	1380215	AL031721.1;UNKL	0;0
cg26530341	chr8	23225840	RP11-1149O23.3;TNFRSF10A	0;54
cg01804429	chr4	68350359	YTHDC1	7
cg03684977	chr17	39737550	GRB7	123
cg11203041	chr12	16347252	MGST1	6
cg00138126	chr20	57711641	PM1PA1;RP5-1059L7.1	17;0
cg13760253	chr8	66020465	DNAJC5B	0
cg03070194	chr1	109668062	GSTM2;GSTM4	9;7
cg15852891	chr5	77639121	OTP	8
cg00400263	chr20	59939146	FAM217B;PPP1R3D	0;0

Table 1 – Top10 mediators. ID corresponds to the CpG probe name. Chromosome and Start are coordinates provided by the Illumina services. Gene Symbol corresponds to genes known to be associated with the CpG probes (Illumina annotation file). Pubmed hits corresponds to the number of output from the search "(Breast cancer) AND ('Gene Symbol')".

189 **Second use case : Gender and multiple sclerosis subtypes.** In this second case study, we con-
190 ducted mediation analysis to explore the role of gene expression in the pathway linking patient
191 gender to the occurrence of Multiple Sclerosis (MS) specific subtypes: Clinically Isolated Syn-
192 drome (CIS) and Relapsing-Remitting (RR). We used the publicly available dataset GSE137143
193 (Kim et al., 2021). This dataset comprises peripheral blood mononuclear cells (PBMCs) from
194 healthy individuals and patients with MS. Upon observing a significant decrease in CIS-MS
195 occurrence among women (see Fig 3A), we sought to investigate this phenomenon further.
196 Although the prevalence of MS is known to be higher in women (Harbo et al., 2013), men
197 tends indeed to present worst disease progression (Voskuhl et al., 2020). We found that being
198 female was associated with a 1.58-fold lower risk of developing Relapsing-Remitting Multiple
199 Sclerosis (Wald-test, $p=0.0036$, $sd = 0.54$). In the original dataset, gene expression was assessed
200 in CD4+, CD8+ T cells, and monocytes. To avoid potential confounding effect from paired data
201 (i.e. different measures on the same individual), we focused solely on CD4+ T cell transcriptome
202 to examine the effect of gene expression in the path between gender and MS subtypes. Our
203 analytical model incorporated X as a binary exposure variable representing gender (0 = male, 1
204 = female), M encompassing 18,010 coding gene expressions, and Y denoting MS subtypes (0 =
205 CIS, 1 = RR).

206
207 We conducted a mediation analysis on gene expression to assess the indirect effect of gen-
208 der on MS subtypes. Due to the small cohort size, we did not identify any significant mediators
209 when applying an FDR control strategy. Alternatively, we opted to perform Gene Set Enrichment
210 Analysis (GSEA) (Korotkevich et al., 2021) to detect biological pathways enriched in our medi-
211 ation analysis (see Fig 3B). We ranked the mediators using the max-squared test P -values and
212 screened the mSigDB Hallmark collection of gene sets (Liberzon et al., 2015). In the Fig 3B, we
213 present the top 10 upregulated pathways identified. It was expected to find hallmarks associated
214 with blood in PBMCs, such as coagulation or heme metabolism. Given the inflammatory nature
215 of MS, it was also reassuring to find immune-related gene sets, such as complement activity or
216 allograft rejection, which correlates with cytolytic activity. Interestingly, we also identified sev-
217 eral pathways previously associated with MS disease that thus appear promising for elucidating

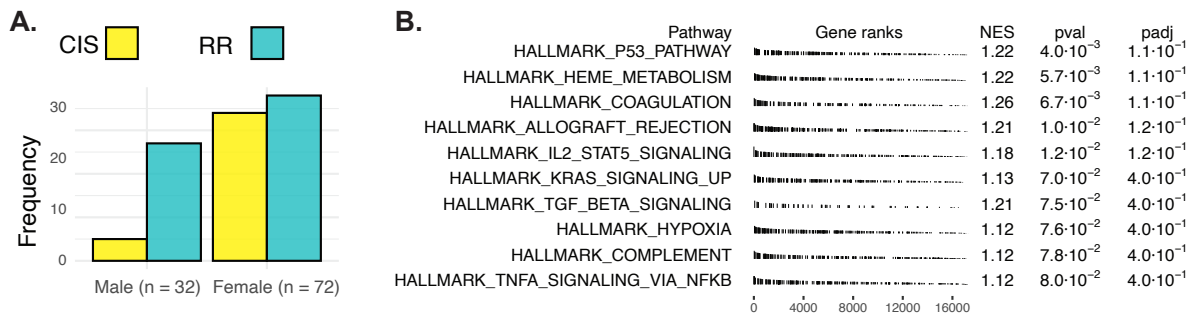


Figure 3 – Effect of gender on MS subtypes. **A.** Barplot of subtype occurrence according to gender. Total number of individual: 104. **B.** The pathways represent the top 10 selected gene sets. Gene ranks were determined using the $-\log_{10}$ of the max-squared P -values. NES (Normalized Enrichment Scores) were computed using the GSEA function. Additionally, P -values (pval) and adjusted P -values (padj) via Benjamini-Hochberg correction were associated with each pathway NES.

218 the causal relationship between gender, gene expression, and MS subtypes: (i) several studies
 219 previously established a link between hypoxia and MS disease progression (Halder and Milner,
 220 2020); (ii) some studies have demonstrated the pivotal role of the interleukin 2 receptor path-
 221 way in autoimmune response, particularly in MS progression (Peerlings et al., 2021), and (iii) p53
 222 has been associated with immune regulation (Muñoz-Fontela et al., 2016). All of these findings
 223 present intriguing avenues for further investigation into the gender impact on MS subtypes.

224 To further investigate the role of top mediators, despite the low level of significance in the
 225 max-squared test, we focused on the top two mediators: *NT5E* (HDMAX2 max-squared P -value
 226 = $5.10 \cdot 10^{-06}$) and *MVB12B* (HDMAX2 max-squared P -value = $2.10 \cdot 10^{-06}$). Interestingly, these medi-
 227 ators exhibit opposite effects on the pathway between gender and MS subtypes (Fig 4). *NT5E* is an
 228 ecto-5'-nucleotidase known to play a role in immune response deregulation in MS. It has been re-
 229 ported that ectonucleotidases are associated with RR MS in relapsing patients (Álvarez-Sánchez
 230 et al., 2019). Notably, *NT5E* expression appears to be elevated in women, thereby increasing the
 231 risk of developing RR MS in this population (ACME = +0.06 with a CI of [0.02,0.14]; PM = 19%
 232 with a CI of [4,97]). On the other hand, *MVB12B* is a member of the ESCRT-1 complex. This
 233 protein was recently identified in a genome-wide protein quantitative trait locus study aimed at
 234 identifying drivers of immune-related diseases (The SCALLOP consortium et al., 2023). In our
 235 study, *MVB12B* was associated with a reduced risk of RR MS in women (ACME = -0.09 with a
 236 CI of [-0.18,-0.02]; PM = 29% with a CI of [5,100]). Note that in this case study, the small sam-
 237 ple size poses challenges in interpreting the estimated confidence intervals, particularly when
 238 calculating mediated proportions. Nonetheless, the mediation study offers valuable indications
 239 into the mediation mechanisms at play. These findings underscore the ability of high-dimensional
 240 analysis to provide insightful understanding into the biological mechanisms underlying observed
 241 statistical associations, even with a small cohort size.

242 Discussion

243 In this article, we introduced the `hdmax2` R package, dedicated to high-dimensional me-
 244 diation analysis. The HDMAX2 method includes unobserved latent factors through a latent
 245 factor mixed model approach. It supports the use of exposures of various types and the

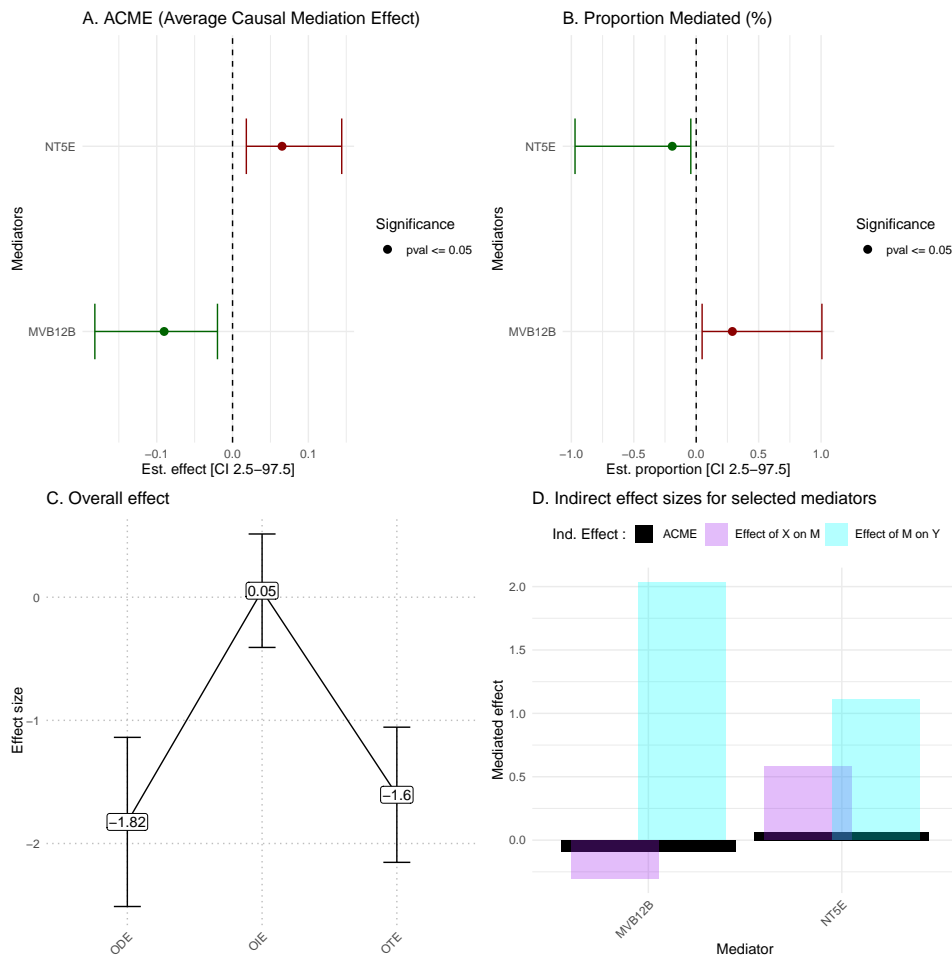


Figure 4 – Summary of the multiple sclerosis use case. **A** Estimates of indirect effect (ACME) and **A** proportions of mediated effect (PM) for the top2 mediators. The effect estimate is represented by a dot and its 95% CI by the bar. Symbols correspond to the significance cut off of 5% (square for P -value ≥ 0.05 , circle P -value < 0.05). Colors correspond to the sign of the effect (green for estimated effect ≤ 0 , red for estimated effect > 0). **C** Effect sizes of Overall Direct Effect (ODE), Overall Indirect Effect (OIE) and Overall Total Effect (OTE). Error bars correspond to standard deviation (ODE and OTE) or confidence interval (OIE). **D** Indirect effect sizes for the selected mediators. Black corresponds to the ACME, violet to the effect of exposure X on mediator M in the model $X \sim M$, and blue corresponds to the effect of mediator M on outcome Y in the model $Y \sim M + X$.

246 consideration of both continuous and binary outcomes. We provide a detailed usage vi-
 247 gnette and showcase the relevance of our approach through transcriptome and methylome
 248 dataset analyses use-cases. The package is available on GitHub for easy access and contribution.
 249

250 While the HDMAX2 method has been optimized for high-dimension analysis, it can natu-
 251 rally be applied outside of this framework, as long as the number of mediators considered is
 252 superior to K (the number of confounders estimated by the latent factor mixed models). The
 253 use cases we propose have been selected for demonstration purposes, taking advantage of
 254 publicly available data. The choice of mediators to consider should be made by the user based
 255 on their specific needs and scientific questions. We provide helper functions in a separate
 256 vignette, allowing for conducting mediator selection under FDR control, or for the aggregation
 257 of P -values to study regions of interest. Aggregated Methylated Regions (AMR) are a typical

258 example of regions of interest, when studying DNA methylation mediated effect. AMR are
259 made of CpG with significant P -value, in a given genomic region, they can be viewed as the
260 parallel of Differentially Methylated Regions in classical EWAS. Although mediation analyses
261 can establish a statistical association between an exposure, a mediator and an outcome, they do
262 not guarantee a causal role in the biological processes observed. The user must then be careful
263 not to over-interpret his results, and to build his models taking into account the sequentiality
264 of the elements observed and the interactions between the different variables included in the
265 model.

266

267 We believe that the HDMAX2 method and its implementation as a package could find wide
268 applications in the fields of epidemiology, as well as in computational biology approaches aimed
269 at gaining deeper insights into the biological background of diseases such as cancer, for which
270 omics datasets are readily available in the public domain. It is worth noting that recent studies
271 have proposed methods for conducting mediation analysis in the context of survival outcomes
272 (Clark-Boucher et al., 2023; Luo et al., 2020; Zhang et al., 2021) . This is a significant demand
273 in healthcare, and we are considering including this capability in the `hdmax2` package once we
274 have conducted a comprehensive analysis of the methodological approach to implement.

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276

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286

Conflict of interest disclosure

287 The authors declare that they comply with the PCI rule of having no financial conflicts of
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289

Data, script, code, and supplementary information availability

290 Data are available online on public repositories. Script and codes are available online: <https://github.com/bcm-uga/hdmax2>.
291

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