A publishing infrastructure for Al-assisted academic authoring

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Abstract

In this work, we investigate the use of advanced natural language processing models to streamline the time-consuming process of writing and revising scholarly manuscripts. For this purpose, we integrate large language models into the Manubot publishing ecosystem to suggest revisions for scholarly texts. Our Al-based revision workflow employs a prompt generator that incorporates manuscript metadata into templates, generating section-specific instructions for the language model. The model then generates revised versions of each paragraph for human authors to review. We evaluated this methodology through three case studies of existing manuscripts, including the revision of this manuscript. Our results indicate that these models, despite some limitations, can grasp complex academic concepts and enhance text quality. All changes to the manuscript are tracked using a version control system, ensuring transparency in distinguishing between human- and machinegenerated text. Given the significant time researchers invest in crafting prose, incorporating large language models into the scholarly writing process can significantly improve the type of knowledge work performed by academics. Our approach also enables scholars to concentrate on critical aspects of their work, such as the novelty of their ideas, while automating tedious tasks like adhering to specific writing styles. Although the use of Al-assisted tools in scientific authoring is controversial, our approach, which focuses on revising human-written text and provides change-tracking transparency, can mitigate concerns regarding Al's role in scientific writing.

Introduction

The tradition of scholarly writing dates back thousands of years, evolving significantly with the advent of scientific journals approximately 350 years ago [1]. External peer review, used by many journals, is even more recent, having been around for less than 100 years [2]. Most manuscripts are written by individuals or teams working together to describe new advances, summarize existing literature, or argue for changes in the status quo. However, scholarly writing is a time-consuming process in which the results of a study are presented using a specific style and format. Academics can sometimes be long-winded in getting to key points, making their writing more impenetrable to their audience [3].

Recent advances in computing capabilities and the widespread availability of text, images, and other data on the internet have laid the foundation for artificial intelligence (AI) models with billions of parameters. Large language models (LLMs), in particular, are opening the floodgates to new technologies with the capability to transform how society operates [4]. OpenAl's models, for instance, have been trained on vast amounts of data and can generate human-like text [5]. These models are based on the transformer architecture which uses self-attention mechanisms to model the complexities of language. The most well-known of these models is the Generative Pre-trained Transformer (GPT-3 and, more recently, GPT-4), which have been shown to be highly effective for a range of language tasks such as generating text, completing code, and answering questions [5]. In the realm of medical informatics, scientists are beginning to explore the utility of these tools in optimizing clinical decision support [6] or assessing its potential to reduce health disparities [7], while also raising concerns about their impact in medical education [8] and the importance of keeping the human aspect central in AI development and application [9]. These tools have been also used in enhancing scientific communication [10]. This technology has the potential to revolutionize how scientists write and revise scholarly manuscripts, saving time and effort and enabling researchers to focus on more high-level tasks such as data analysis and interpretation. However, the use of LLMs in research has sparked controversy, primarily due to their propensity to generate plausible yet factually incorrect or misleading information.

In this work, we present a human-centric approach for the use of AI in manuscript writing where scholarly text, initially created by humans, is revised through edit suggestions from LLMs, and is

ultimately reviewed and approved by humans. This approach mitigates the risk of generating misleading information while still providing the benefits of Al-assisted writing. We developed an Al-assisted revision tool that implements this approach and builds on the Manubot infrastructure for scholarly publishing [11], a platform designed to enable both individual and large-scale collaborative projects [12,13]. Our tool, named the Manubot Al Editor, parses the manuscript, utilizes an LLM with section-specific prompts for revision, and then generates a set of suggested changes to be integrated into the main document. These changes are presented to the user through the GitHub interface for review. During prompt engineering, we developed unit tests to ensure that a minimum set of quality measures are met by the Al revisions. For end-to-end evaluation, we manually reviewed the Al revisions on three Manubot-authored manuscripts that included sections of varying complexity. Our findings indicate that, in most cases, the models were able to maintain the original meaning of text, improve the writing style, and even interpret mathematical expressions. Officially part of the Manubot platform, our Manubot Al Editor can be readily incorporated into Manubot-based manuscripts, and we anticipate it will help authors more effectively communicate their work.

Implementing Al-based revision into the Manubot publishing ecosystem

We propose a human-centric approach for the use of AI in manuscript writing, which consists of the following steps: 1) human authors write the manuscript content; 2) an LLM revises the manuscript, generating a set of suggested changes; 3) human authors review the suggested changes, and the approved edits are then integrated into the manuscript. By focusing on human review, this approach attempts to mitigate the risk of generating incorrect or misleading information. To implement this human-centric approach, we developed a tool called the Manubot AI Editor, which is part of the Manubot infrastructure for scholarly publishing [11].

Overview of the Manubot AI Editor

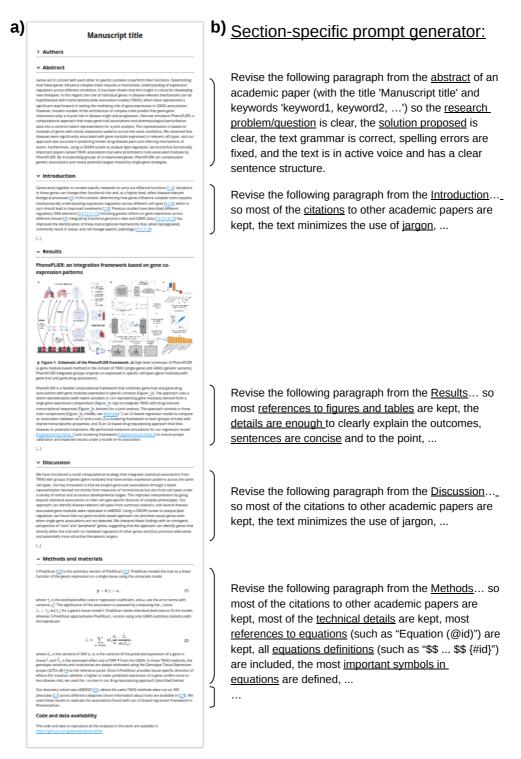


Figure 1: Al-based revision applied on a Manubot-based manuscript. a) A manuscript (written with Manubot) with different sections. **b)** The prompt generator integrates metadata using prompt templates to generate section-specific prompts for each paragraph. If a paragraph belongs to a non-standard section, then a default prompt will be used to perform a basic revision only. The prompt for the Methods section includes the formatting of equations with identifiers. All sections' prompts include these instructions: "the text grammar is correct, spelling errors are fixed, and the text has a clear sentence structure", although these are only shown for abstracts. Our tool allows the user to provide a custom prompt instead of using the default ones shown here.

The Manubot AI Editor is an AI-based revision infrastructure built into Manubot [11], a tool for collaborative writing of scientific manuscripts. Manubot integrates with popular version control platforms such as GitHub, allowing authors to easily track changes and collaborate on writing in real time. Furthermore, Manubot automates the process of generating a formatted manuscript (e.g., HTML, PDF, DOCX; Figure 1a shows the HTML output). Built on this modern and open paradigm, our Manubot AI Editor (https://github.com/manubot/manubot-ai-editor) includes three components: 1) a Python library that provides classes and functions to read the manuscript content and its metadata,

calls the LLM for automatic text revision, and writes the results back; 2) a GitHub Actions workflow that uses our Python library within GitHub to preserve provenance information for transparency; 3) a prompt generator that integrates the manuscript's metadata using prompt templates to generate section-specific prompts for each paragraph (Figure 1b).

The GitHub Actions workflow allows users to easily trigger an automated revision task on the entire manuscript or specific sections of it. When the action is triggered, the manuscript is parsed by section and then by paragraph (Figure 1b), which are passed to the language model along with a set of custom prompts. The model then returns a revised version of the text. Our workflow uses the GitHub API to generate a new pull request, allowing the user to review and modify the output before merging the changes into the manuscript. This workflow attributes text to either the human user or the AI language model, which may be important in light of potential future legal decisions that could alter the copyright landscape around the outputs of generative models.

We used the <u>OpenAl API</u> for access to these models. Since this API incurs a cost with each run that depends on manuscript length, we implemented a workflow in GitHub Actions that can be manually triggered by the user. Our implementation allows users to tune the costs to their needs by enabling them to select specific sections for revision instead of the entire manuscript. Additionally, several model parameters can be adjusted to further tune costs, such as the language model version (including Davinci and Curie, the current GPT-3.5 Turbo and GPT-4, and potentially newly published ones), how much risk the model will take, or the "quality" of the completions. For instance, using Davinci models, the cost per run is under \$0.50 for most manuscripts.

Implementation details

To run the workflow, the user must specify the branch that will be revised, select the files/sections of the manuscript (optional), specify the language model to use (text-davinci-003 by default), an optional custom prompt (section-specific prompts are used by default), and provide the output branch name. For more advanced users, it is also possible to change most of the tool's behavior or the language model parameters.

When the workflow is triggered, it downloads the manuscript by cloning the specified branch. It revises all of the manuscript files, or only some of them if the user specifies a subset. Next, each paragraph in the file is read and submitted to the OpenAl API for revision. If the request is successful, the tool will write the revised paragraph in place of the original one, using one sentence per line (which is the recommended format for the input text). If the request fails, the tool might try again (up to five times by default) if it is a common error (such as "server overloaded") or a model-specific error that requires changing some of its parameters. If the error cannot be handled or the maximum number of retries is reached, the original paragraph is written instead with an HTML comment at the top explaining the cause of the error. This allows the user to debug the problem and attempt to fix it if desired.

As shown in Figure 1b, each API request comprises a prompt (the instructions given to the model) and the paragraph to be revised. Unless the user specifies a custom prompt, the tool will use a section-specific prompt generator that incorporates the manuscript title and keywords. Therefore, both must be accurate to obtain the best revision outcomes. The other key component to process a paragraph is its section. For instance, the abstract is a set of sentences with no citations, whereas a paragraph from the Introduction section has several references to other scientific papers. A paragraph in the Results section has fewer citations but many references to figures or tables, and must provide enough details about the experiments to understand and interpret the outcomes. The Methods section is more dependent on the type of paper, but in general, it has to provide technical details and sometimes mathematical formulas and equations. Therefore, we designed section-specific prompts, which we found led to the most useful suggestions. Figure and table captions, as well as paragraphs that

contain only one or two sentences and fewer than sixty words, are not processed and are copied directly to the output file.

The section of a paragraph is automatically inferred from the file name using a simple strategy, such as if "introduction" or "methods" is part of the file name. If the tool fails to infer a section from the file, the user can still specify to which section the file belongs. The section can be a standard one (abstract, introduction, results, methods, or discussion) for which a specific prompt is used (Figure 1b), or a non-standard one for which a default prompt is used to instruct the model to perform basic revision. This includes "minimizing the use of jargon, ensuring text grammar is correct, fixing spelling errors, and making sure the text has a clear sentence structure."

Properties of language models

The Manubot Al Editor uses the <u>Chat Completions API</u> to process each paragraph. We have tested our tool using both the Davinci and Curie models, including text-davinci-003, text-davinci-edit-001, and text-curie-001. Within the GPT-3 family, the Davinci models are the most powerful, while the Curie models are less capable but faster and less expensive. All models can be fine-tuned using different parameters (refer to <u>OpenAl - API Reference</u>), and the most important ones can be easily adjusted using our tool.

Language models for text completion have a context length that indicates the limit of tokens they can process (tokens are common character sequences in text). This limit includes the size of the prompt and the paragraph, as well as the maximum number of tokens to generate for the completion (parameter max_tokens). For instance, the context length of Davinci models is 4,000 and for Curie, it is 2,048 (see OpenAI - Models overview). To ensure we never exceed this context length, our AIassisted revision software processes each paragraph of the manuscript with section-specific prompts, as shown in Figure 1b. This approach allows us to process large manuscripts by breaking them into smaller chunks of text. However, since the language model only processes a single paragraph from a section, it can potentially lose important context needed to produce a better output. Nonetheless, we find that the model still produces high-quality revisions (see Results). Additionally, the maximum number of tokens (parameter max_tokens) is set as twice the estimated number of tokens in the paragraph (one token approximately represents four characters, see OpenAl - Tokenizer). The tool automatically adjusts this parameter and performs the request again if a related error is returned by the API. The user can also force the tool to either use a fixed value for max_tokens for all paragraphs, or change the fraction of maximum tokens based on the estimated paragraph size (two by default).

The language models used are stochastic, meaning they generate a different revision for the same input paragraph each time. This behavior can be adjusted by using the "sampling temperature" or "nucleus sampling" parameters (we use temperature=0.5 by default). Although we selected default values that work well across multiple manuscripts, these parameters can be changed to make the model more deterministic. The user can also instruct the model to generate several completions and select the one with the highest log probability per token, which can improve the quality of the revision. Our implementation generates only one completion (parameter best_of=1) to avoid potentially high costs for the user. Additionally, our workflow allows the user to process either the entire manuscript or individual sections. This provides more cost-effective control while focusing on a single piece of text, wherein the user can run the tool several times and pick the preferred revised text.

Installation and use

The Manubot AI Editor is part of the standard Manubot template manuscript, referred to as rootstock, and is available at https://github.com/manubot/rootstock. Users wishing to use the workflow only need to follow the standard procedures to install Manubot. The section "AI-assisted authoring", found in the file USAGE.md of the rootstock repository, explains how to enable the tool. Afterward, the workflow (named ai-revision) will be available and ready to use under the Actions tab of the user's manuscript repository.

Evaluations of AI-based revisions

Evaluation setup

Assessing the performance of text generation tasks is challenging, and this is especially true for automatic revisions of scientific content. In this context, we need to make sure the revision does not change the original meaning or introduce incorrect or misleading information. For this reason, our approach emphasizes human assessments of the revisions to mitigate these issues, and we followed the same procedure in evaluating our tool. We used three manuscripts of our own authorship (see below), which allowed us to more objectively assess changes in the original meaning and whether revisions retained important details. During the prompt engineering phase (see below), we also used a unit testing framework to ensure that the revisions produced by our prompts met a minimum set of quality measures.

Language models

We evaluated our Al-assisted revision workflow using three GPT-3 models from OpenAl: text-davinci-003, text-davinci-edit-001, and text-curie-001. The first two are based on the most capable GPT-3 Davinci models (see OpenAl-GPT-3 models). Whereas text-davinci-003 is a production-ready model for the completion endpoint, text-davinci-edit-001 is used for the edits endpoint and was still in beta at the time of testing. The latter provides a more natural interface for revising manuscripts, as it takes two inputs: instructions and the text to revise. The text-curie-001 model is faster and cheaper than the Davinci models and is defined as "very capable" by its authors (see OpenAl-GPT-3 models).

Manuscripts

Table 1: Manuscripts used to evaluate the AI-based revision workflow. The title and keywords of a manuscript are used in prompts for revising paragraphs. IDs are used in the text to refer to them.

Manuscript ID	GitHub URL	Title	Keywords
CCC	greenelab/ccc- manuscript	An efficient not-only-linear correlation coefficient based on machine learning	correlation coefficient, nonlinear relationships, gene expression
PhenoPLIER	greenelab/phenoplier m anuscript	Projecting genetic associations through gene expression patterns highlights disease etiology and drug mechanisms	genetic studies, functional genomics, gene co-expression, therapeutic targets, drug repurposing, clustering of complex traits
Manubot-Al	greenelab/manubot-gpt- manuscript	A publishing infrastructure for Al-assisted academic authoring	manubot, artificial intelligence, scholarly publishing, software

The evaluation of our tool was conducted using three of our own manuscripts (Table 1): the Clustermatch Correlation Coefficient (CCC) [14], PhenoPLIER [15], and Manubot-Al (this manuscript). CCC is a new correlation coefficient applied to transcriptomic data, while PhenoPLIER is a framework consisting of three different methods used in genetic studies. CCC falls under the field of computational biology, whereas PhenoPLIER pertains to genomic medicine. CCC outlines one computational method applied to a specific data type (correlation to gene expression). In contrast, PhenoPLIER describes a framework that integrates three different approaches (regression, clustering, and drug-disease prediction) using data from genome-wide and transcription-wide association studies (GWAS and TWAS), gene expression, and transcriptional responses to small molecule perturbations. Thus, CCC has a simpler structure, while PhenoPLIER is a more complex manuscript with additional figures and tables, along with a Methods section that includes equations. The third manuscript, Manubot-Al, has a much simpler structure and was written and revised using our tool prior to submission, demonstrating a practical Al-based revision use case.

Evaluation using human assessments

We enabled the Manubot AI revision workflow in the GitHub repositories of the three manuscripts (CCC, PhenoPLIER, and Manubot-AI). This added the "ai-revision" workflow to the "Actions" tab of each repository. We triggered the workflow manually and used the three language models described above to produce one pull request (PR) per manuscript and model. These PRs can be accessed from the "Pull requests" tab of each repository. They are titled "GPT (MODEL) used to revise manuscript", with MODEL being the identifier of the model used. The PRs show all the differences between the original text and the AI-based revision suggestions.

When manually assessing the quality of the revisions, we considered whether the revision: 1) preserve the original meaning, 2) preserve important details, 4) introduced new and incorrect information, and 5) preserve the correct Markdown format (e.g., citations, equations).

Prompt engineering

We extensively tested our tool, including prompts, using a unit testing framework. Our unit tests cover the general processing of the manuscript content (such as splitting by paragraphs), the generation of custom prompts using the manuscript metadata, and writing back the text suggestions (ensuring that the original style is preserved as much as possible to minimize the number of changes). More importantly, they also cover some basic quality measures of the revised text. This latter set of unit tests was used during our prompt engineering work, and they ensure that section-specific prompts yield revisions with a minimum set of quality measures. For instance, we wrote unit tests to check that revised Abstracts consist of a single paragraph, start with a capital letter, end with a period, and that no citations to other articles are included. For the Introduction section, we check that a certain percentage of citations are kept, which also attempts to give the model some flexibility to remove text deemed unnecessary. We found that adding the instruction "most of the citations to other academic papers are kept" to the prompt was enough to achieve this with the most capable model. We also wrote unit tests to ensure the models returned citations in the correct Manubot/Markdown format (e.g., [@doi:...] or [@arxiv:...]), and found that no changes to the prompt were needed for this (i.e., the model automatically detected the correct format in most cases). For the Results section, we included tests with short inline formulas in LaTeX (e.g., \$\gamma_l\$) and references to figures, tables, equations, or other sections (e.g., Figure @id or Equation (@id)) and found that, in the majority of cases, the most capable model was able to correctly keep them with the right format. For the Methods section, in addition to the aforementioned tests, we also evaluated the ability of models to use the correct format for the definition of numbered, multiline equations, and found that the most capable model succeeded in most cases. For this particular case, we needed to modify our prompt to explicitly mention the correct format of multiline equations (see prompt for Methods in Figure 1).

We also included tests where the model is expected to fail in generating a revision (for instance, when the input paragraph is too long for the model's context length). In these cases, we ensure that the tool returns a proper error message. We ran our unit tests across all models under evaluation.

General assessment of language models

Our initial human assessments across the three manuscripts and unit tests revealed that, although faster and less expensive, the Curie model was unable to produce acceptable revisions for any of the manuscripts. The PRs show that most of its suggestions were not coherent with the original text in any of the manuscript sections. The model clearly could not understand the revision instructions; in most cases, it did not produce a meaningful revision, replaced the text with the instructions, added the title of the manuscript at the beginning of the paragraph, consistently failed to keep citations to other articles (especially in the Introduction section), or added content that was not present in the original text. In addition, for similar reasons, we found that the quality of the revisions produced by the text-davinci-edit-001 model (edits endpoint) was inferior to those produced by the text-davinci-003 model (completion endpoint). This might be because, at the time of testing, the edits endpoint was still in beta. The text-davinci-003 model produced the best results for all manuscripts and across the different sections, leading us to focus on the text-davinci-003 model for the rest of the evaluation below.

Revision of different sections

Following our criteria (see above), we inspected the PRs generated by the Al-based workflow and report on our assessment of the changes suggested by the tool across different sections of the manuscripts. The reader can access the PRs in the manuscripts' GitHub repositories (Table 1) and also included as diff files in Supplementary File 1 (CCC), 2 (PhenoPLIER) and 3 (Manubot-Al).

Below, we present the differences between the original text and the revisions by the tool in a diff format (obtained from GitHub). Line numbers are included to show the length differences. Unless the Al suggestions represent a complete overhaul of the text, single words are underlined and highlighted in colors to more clearly see the differences within a single sentence. Red indicates words removed by the tool, green indicates words added, and no underlining indicates words kept unchanged. In the GitHub repositories, the full diffs can be seen by clicking on the "Files changes" tab under each PR.

Abstract

- Correlation coefficients are widely used to 1 + This paper presents the Clustermatch identify patterns in data that may be of Correlation Coefficient (CCC), an efficient and not-only-linear correlation coefficient particular interest. based on machine learning models, to identify linear and nonlinear patterns in transcriptomics data. - In transcriptomics, genes with correlated 2 + We aim to determine if CCC can detect expression often share functions or are part meaningful linear and nonlinear relationships of disease-relevant biological processes. in gene expression data, including those missed by linear-only correlation coefficients, and if highly-ranked gene pairs by CCC are enriched for interactions in - Here we introduce the Clustermatch Correlation 3 | + When applied to human gene expression data, Coefficient (CCC), an efficient, easy-to-use CCC identifies robust linear relationships and and not-only-linear coefficient based on nonlinear patterns associated with sex machine learning models. - CCC reveals biologically meaningful linear and 4 + Our results suggest that CCC can detect nonlinear patterns missed by standard, linearfunctional relationships not captured by only correlation coefficients. linear-only methods. - CCC captures general patterns in data by 5 + CCC is a highly-efficient, next-generation comparing clustering solutions while being not-only-linear correlation coefficient that can be applied to genome-scale data and other much faster than state-of-the-art coefficients such as the Maximal Information Coefficient. domains across different data types. - When applied to human gene expression data. CCC identifies robust linear relationships while detecting nonlinear patterns associated. for example, with sex differences that are not captured by linear-only coefficients. - Gene pairs highly ranked by CCC were enriched for interactions in integrated networks built from protein-protein interaction, transcription factor regulation, and chemical and genetic perturbations, suggesting that CCC could detect functional relationships that linear-only methods missed. - CCC is a highly-efficient, next-generation not-only-linear correlation coefficient that can readily be applied to genome-scale data and other domains across different data types.

Figure 2: Abstract of CCC. Original text is on the left and suggested revision on the right. Single words are not underlined/highlighed in this case because the revision completely overhauled the text.

We applied the AI-based revision workflow to the CCC abstract (Figure 2). The tool completely rewrote the text, leaving only the last sentence mostly unchanged. The text was significantly shortened, and the sentences were longer than those in the original, which could make the abstract slightly harder to read. The revision removed the first two sentences, which introduced correlation analyses and transcriptomics, and directly stated the purpose of the manuscript. It also removed details about the method (line 5), and focused on the aims and results obtained, ending with the same last sentence, suggesting a broader application of the coefficient to other data domains (as originally intended by the authors of CCC). The main concepts were still present in the revised text.

The revised text for the abstract of PhenoPLIER was significantly shortened (from 10 sentences in the original, to only 3 in the revised version). However, in this case, important concepts (such as GWAS, TWAS, CRISPR) and a proper amount of background information were missing, producing a less informative abstract.

Introduction

New technologies have vastly improved data 1 | + The increasing availability of data has opened up new possibilities for scientific collection, generating a deluge of information across different disciplines. exploration. - This large amount of data provides new 2 + To take advantage of this, we need efficient opportunities to address unanswered scientific tools to identify multiple types of questions, provided we have efficient tools relationships between variables. capable of identifying multiple types of underlying patterns. - Correlation analysis is an essential 3 + Correlation analysis is a useful statistical statistical technique for discovering technique to uncover such relationships relationships between variables [@pmid:21310971]. - Correlation coefficients are often used in 4 + Correlation coefficients are often used in exploratory data mining techniques, such as data mining techniques, such as clustering or clustering or community detection algorithms, community detection, to calculate the similarity between two objects, like genes to compute a similarity value between a pair of objects of interest such as genes [@pmid:27479844] or lifestyle factors related [@pmid:27479844] or disease-relevant lifestyle to diseases [@doi:10.1073/pnas.1217269109]. factors [@doi:10.1073/pnas.1217269109]. - Correlation methods are also used in 5 + They are also used in supervised tasks, like supervised tasks, for example, for feature feature selection, to boost prediction accuracy [@pmid:27006077; @pmid:33729976]. selection to improve prediction accuracy [@pmid:27006077; @pmid:33729976]. - The Pearson correlation coefficient is 6 + The Pearson correlation coefficient is widely used across many application domains and ubiquitously deployed across application domains and diverse scientific areas. scientific disciplines. - Thus, even minor and significant improvements 7 | + Therefore, even small improvements in this in these techniques could have enormous technique can have a huge impact on industry consequences in industry and research. and research.

Figure 3: First paragraph in the Introduction section of CCC. Original text is on the left and suggested revision on the right.

The tool significantly revised the Introduction section of CCC (Figure 3), producing a more concise and clear introductory paragraph. The revised first sentence concisely incorporated ideas from the original two sentences, introducing the concept of "large datasets" and the opportunities for scientific exploration. The model generated a more concise second sentence introducing the "need for efficient tools" to find "multiple relationships" in these datasets. The third sentence connected nicely with the previous one. All references to scientific literature were kept in the correct Manubot format, even though our prompts do not specify the references format. The rest of the sentences in this section were also correctly revised and could be incorporated into the manuscript with minor or no further changes.

We also observed a high-quality revision of the introduction of PhenoPLIER. However, the model failed to maintain the format of citations in one paragraph. Additionally, the model did not converge to a revised text for the last paragraph, and our tool left an error message as an HTML comment at the top: The AI model returned an empty string. Debugging the prompts revealed this issue, which could be related to the complexity of the paragraph. In these cases, rerunning the automated revision might solve this type of issue.

Results

- We simulated additional types of relationships 1 + Simulations of additional types of relationships (Figure @fig:datasets_rel, second row), including (Figure @fig:datasets_rel, second row), including some previously described from gene expression some previously described from gene expression data [@doi:10.1126/science.1205438; data [@doi:10.1126/science.1205438; @doi:10.3389/fgene.2019.01410; @doi:10.3389/fgene.2019.01410; @doi:10.1091/mbc.9.12.3273]. [adoi:10.1091/mbc.9.12.3273], showed that for random/independent variables, all coefficients correctly agreed with a value close to zero. - For the random/independent pair of variables, all 2 + The non-coexistence pattern, captured by all coefficients correctly agree with a value close to coefficients, represented a case where one gene (\$x\$) is expressed while the other one (\$y\$) is inhibited, highlighting a potentially strong biological relationship (such as a microRNA negatively regulating another gene). 3 + Pearson and Spearman did not capture the nonlinear - The non-coexistence pattern, captured by all coefficients, represents a case where one gene patterns between variables \$x\$ and \$v\$ in the (\$x\$) might be expressed while the other one (\$y\$) quadratic and two-lines examples, while CCC increased the complexity of the model by using is inhibited, highlighting a potentially strong biological relationship (such as a microRNA different degrees of complexity to capture the negatively regulating another gene). 4 + For the quadratic pattern, CCC used four clusters - For the other two examples (quadratic and twolines), Pearson and Spearman do not capture the for \$x\$ and achieved the maximum ARI. nonlinear pattern between variables \$x\$ and \$y\$. 5 + In the two-lines example, CCC used eight clusters - These patterns also show how CCC uses different degrees of complexity to capture the for \$x\$ and six for \$y\$, resulting in \$c=0.31\$, while Pearson and Spearman gave \$p=-0.12\$ and \$s=0.05\$, respectively. - For the quadratic pattern, for example, CCC separates \$x\$ into more clusters (four in this case) to reach the maximum ARI. - The two-lines example shows two embedded linear relationships with different slopes, which neither Pearson nor Spearman detect (\$p=-0.12\$ and \$s=0.05\$, respectively). - Here, CCC increases the complexity of the model by using eight clusters for \$x\$ and six for \$v\$. resulting in \$c=0.31\$.

Figure 4: A paragraph in the Results section of CCC. Original text is on the left and suggested revision on the right. Single words are not underlined/highlighed in this case because the revision completely overhauled the text.

We tested the tool on a paragraph from the Results section of CCC (Figure 4). This paragraph describes Figure 1 of the CCC manuscript [14], which showcases four different datasets, each with two variables, and various relationships or patterns labeled as random/independent, non-coexistence, quadratic, and two-lines. The revised paragraph, while having fewer sentences, is slightly longer and consistently uses past tense, unlike the original one which has tense shifts. The revised paragraph also retains all citations, which, although not explicitly mentioned in the prompts for this section (as it is for introductions), is important in this case. The original LaTeX format was maintained for the math and the figure was correctly referenced using the Manubot syntax. In the third sentence of the revised paragraph (line 3), the model generated a good summary of how all coefficients performed in the last two nonlinear patterns, and why CCC was able to capture them. As human authors, we would make a single change at the end of this sentence to avoid repeating the word "complexity": "..., while CCC increased the model's complexity by using different degrees of complexity to capture the relationships." The revised paragraph is more concise and clearly describes what the figure shows and how CCC works. It's remarkable that the model rewrote some of the concepts in the original paragraph (lines 4 to 8) into three new sentences (lines 3 to 5) with the same meaning, but more concisely and clearly. The model also produced high-quality revisions for several other paragraphs that would only need minor changes.

However, other paragraphs in CCC required extensive changes before they could be incorporated into the manuscript. For instance, the model generated revised text for certain paragraphs that was more concise, direct, and clear. However, this often resulted in the removal of important details and occasionally altered the intended meaning of sentences. To address this issue, we could accept the simplified sentence structure proposed by the model, but reintroduce the missing details for clarity and completeness.

- Our first experiment attempted to answer 1 + We conducted a gene co-expression analysis to identify potential therapeutic targets for whether genes in a disease-relevant LV could lipid regulation ([Methods] represent potential therapeutic targets. (#sec:methods:coexp)). 2 + This analysis revealed two clusters of genes - For this, the first step was to obtain a set of genes strongly associated with a phenotype associated with lipid regulation: a cluster of genes associated with decreased lipids (cluster 1) and a cluster of genes associated with increased lipids (cluster 2). 3 + We found that the genes in our high-confidence - Therefore, we performed a fluorescence-based CRISPR-Cas9 in the HepG2 cell line and gene sets were strongly associated with their identified 462 genes associated with lipid respective clusters (Figure 1). regulation ([Methods](#sec:methods:crispr)). 4 + This result suggests that the genes in our - From these, we selected two high-confidence gene sets that either caused a decrease or high-confidence gene sets may represent increase of lipids: potential therapeutic targets for lipid regulation. 5 - a lipids-decreasing gene-set with eight genes: *BLCAP*, *FBXW7*, *INSIG2*, *PCYT2*, *PTEN*, *SOX9*, *TCF7L2*, *UBE2J2*; - and a lipids-increasing gene-set with six genes: *ACACA*, *DGAT2*, *HILPDA*, *MBTPS1*, *SCAP*, *SRPR* (Supplementary File 2).

Figure 5: A paragraph in the Results section of PhenoPLIER. Original text is on the left and suggested revision on the right. Single words are not underlined/highlighed in this case because the revision completely overhauled the text.

When applied to the PhenoPLIER manuscript, the model produced high-quality revisions for most paragraphs while preserving citations and references to figures, tables, and other sections of the manuscript in the Manubot/Markdown format. In some cases, important details were missing, but they could be easily added back while preserving the improved sentence structure of the revised version. In other cases, the model's output demonstrated the limitations of revising one paragraph at a time without considering the rest of the text. For instance, one paragraph described our CRISPR screening approach to assess whether top genes in a latent variable (LV) could represent good therapeutic targets. The model generated a paragraph with a completely different meaning (Figure 5). It omitted the CRISPR screen and the gene symbols associated with the regulation of lipids, which were key elements in the original text. Instead, the new text describes an experiment that does not exist with a reference to a non-existent section. This suggests that the model focused on the title and keywords of the manuscript (Table 1) that were part of every prompt (Figure 1). For example, it included the idea of "gene co-expression" analysis (a keyword) to identify "therapeutic targets" (another keyword) and replaced the mention of "sets of genes" in the original text with "clusters of genes" (closer to the keyword including "clustering"). This was a poor model-based revision, indicating that the original paragraph may be too short or disconnected from the rest and could be merged with the next one, which describes follow-up and related experiments.

Discussion

In both the CCC and PhenoPLIER manuscripts, revisions to the discussion section appeared to be of high quality. The model kept the correct format when necessary (e.g., using italics for gene symbols), maintained most of the citations, and improved the readability of the text in general. Revisions for some paragraphs introduced minor mistakes that a human author could readily fix.

- Not-only-linear correlation coefficients might 1 | + Not-only-linear correlation coefficients may also be helpful in the field of genetic be useful in genetic studies. studies. - In this context, genome-wide association 2 + Genome-wide association studies (GWAS) have been successful in understanding the studies (GWAS) have been successful in understanding the molecular basis of common connection between genotype and phenotype, but diseases by estimating the association between the estimated effect sizes of the identified genotype and phenotype genes are usually small, and they explain only a small part of the phenotype variance [@doi:10.1016/j.ajhg.2017.06.005]. [@doi:10.1016/j.ajhg.2017.06.005; @doi:10.1038/s41576-019-0127-1]. - However, the estimated effect sizes of genes 3 + This has hindered the clinical translation of identified with GWAS are generally modest, and these findings. they explain only a fraction of the phenotype variance, hampering the clinical translation of these findings [@doi:10.1038/s41576-019-- Recent theories, like the omnigenic model for 4 + The omnigenic model for complex traits complex traits [@pmid:28622505; [@pmid:28622505; @pmid:31051098] suggests that @pmid:31051098]<mark>, argue</mark> that these observations highly-interconnected gene regulatory networks are explained by highly-interconnected gene could explain this, with some core genes regulatory networks, with some core genes having a more direct effect on the phenotype having a more direct effect on the phenotype than others. 5 + We and others [@doi:10.1101/2021.07.05.450786; - Using this omnigenic perspective, we and others [@doi:10.1101/2021.07.05.450786; @doi:10.1186/s13040-020-00216-9; @doi:10.1101/2021.10.21.212653421 have @doi:10.1186/s13040-020-00216-9: @doi:10.1101/2021.10.21.21265342] have shown demonstrated that integrating gene cothat integrating gene co-expression networks expression networks in genetic studies could in genetic studies could potentially identify potentially identify core genes that are not found with linear-only models such as GWAS. core genes that are missed by linear-only models alone like GWAS. - Our results <mark>suggest</mark> that <mark>building these</mark> 6 + Our results indicate that using more advanced networks with more advanced and efficient and efficient correlation coefficients to networks with more advanced and efficient correlation coefficients could better estimate build these networks could better estimate gene co-expression profiles and thus more gene co-expression profiles and thus more accurately identify these core genes. accurately identify these core genes. - Approaches like CCC could play a significant 7 + Approaches like CCC could have a significant role in the precision medicine field by role in the precision medicine field by role in precision medicine by providing the computational tools to focus on computational tools to focus on more promising role in precision medicine by providing the genes<mark>, which may represent</mark> better candidate more promising genes representing potentially better candidate drug targets. drug targets.

Figure 6: A paragraph in the Discussion section of CCC. Original text is on the left and suggested revision on the right.

One paragraph from CCC discusses how not-only-linear correlation coefficients could potentially impact genetic studies of complex traits (Figure 6). Although some minor changes could be incorporated, we believe the revised text reads better than the original. It is also interesting to see how the model understood the format of citations and built more complex structures from it. For instance, the two articles referenced in lines 2 and 3 in the original text were correctly merged into a single citation block and separated with a ";" in line 2 of the revised text.

Methods

Prompts for the Methods section were the most challenging to design, especially when the sections included equations. The prompt for Methods (Figure 1) is more focused in keeping the technical details, which was especially important for PhenoPLIER, whose Methods section contains paragraphs with several mathematical expressions.

- S-Predixcan [@doi:10.1038/s41467-018-03621-1] is the summary version of Predixcan [@doi:10.1038/ng.3367]. - Predixcan models the trait as a linear function of the gene's expression on a single tissue using the univariate model 3 4 \$\$ \mathbf{y} = \mathbf{t}_l \gamma_l + \bm{\epsilon}_l, \mathbf{y} = \mathbf{y} = \mathbf{t}_l \gamma_l + \mathbf{y} = \mat
[@doi:10.1038/ng.3367]. [@doi:10.1038/ng.3367], which models the trait as a linear function of the gene's expression on a single tissue using the univariate model: 2 - Predixcan models the trait as a linear function of the gene's expression on a single tissue using the univariate model: 3
as a linear function of the gene's expression on a single tissue using the univariate model: 2 - PrediXcan models the trait as a linear function of the gene's expression on a single tissue using the univariate model: 3
on a single tissue using the univariate model: - PrediXcan models the trait as a linear function of the gene's expression on a single tissue using the univariate model: 3 4 \$\$ 5 \mathbf{y} = \mathbf{t}_\lambda \gamma_\lambda + \mathbf{t}_\lambda \mathbf{t}_\lambda \gamma_\lambda + \mathbf{t}_\lambda \gamma_\lambda \qqq \
2 - Predixcan models the trait as a linear function of the gene's expression on a single tissue using the univariate model 3
function of the gene's expression on a single tissue using the univariate model 3
tissue using the univariate model 3
3
4 \$\$
5 $\mathbb{Y} = \mathbb{Y}_1 \ \mathbb{Y} = \mathbb{Y}_1 \ \mathbb{Y}_2 \ \mathbb{Y}_1 \ \mathbb{Y}_2 \ Y$
\bm{\epsilon}_l, \bm{\epsilon}_l,
6 \$\$ {#eq:predixcan} 5 \$\$ {#eq:predixcan}
7
8 - where \$\gamma_l\$ is the estimated effect 7 + where \$\gamma_l\$ is the estimated effect size
size or regression coefficient, and or regression coefficient, and
\$\bm{\epsilon}_l\$ are the error terms with \$\bm{\epsilon}_l\$ are the error terms with
<pre>variance \$\sigma_{\epsilon}^{2}\$.</pre> variance \$\sigma_{\epsilon}^{2}\$.
9 The significance of the association is 8 The significance of the association is
assessed by computing the \$z\$-score assessed by computing the \$z\$-score
$\hat{z}_{l}=\hat{\gamma}_{l}=\hat$
(\hat{\gamma}_l)\$ for a gene's tissue model (\hat{\gamma}_l)\$ for a gene's tissue model
\$1\$.
10 - PrediXcan needs individual-level data to fit 9 + Whereas PrediXcan requires individual-level
this model, whereas S-Predixcan approximates data to fit this model, S-Predixcan
PrediXcan \$2\$-scores using only GWAS summary approximates PrediXcan \$2\$-scores using only
statistics with the expression GWAS summary statistics with the expression.
11 10
12 \$\$ 11 \$\$
12
13 $\hat{z}_{l} 12 12 12 12 12 12 12 $

Figure 7: A paragraph in the Methods section of PhenoPLIER. Original text is on the left and suggested revision on the right.

We revised a paragraph in PhenoPLIER that contained two numbered equations (Figure 7). The model made very few changes, and all the equations, citations, and most of the original text were preserved. However, we found it remarkable how the model identified a wrong reference to a mathematical symbol (line 8) and fixed it in the revision (line 7). Indeed, the equation with the univariate model used by PrediXcan (lines 4-6 in the original) includes the *true* effect size γ_l (\gamma_l) instead of the *estimated* one $\hat{\gamma}_l$ (\hat{\gamma}_l).

In PhenoPLIER, we found one large paragraph with several equations that the model failed to revise, although it performed relatively well in revising the rest of the section. In CCC, the revision of this section was good overall, with some minor and easy-to-fix issues as in the other sections.

We also observed issues arising from revising one paragraph at a time without context. For instance, in PhenoPLIER, one of the first paragraphs mentions the linear models used by S-PrediXcan and S-MultiXcan without providing any equations or details. These were presented in the following paragraphs, but since the model had not yet encountered that information, it opted to add those equations immediately (in the correct Manubot/Markdown format).

1	- We implemented the AI-based revision infrastructure in Manubot [@doi:10.1371/journal.pcbi.1007128].	1	 + We implemented an AI-based revision infrastructure in Manubot [@doi:10.1371/journal.pcbi.1007128], a tool for collaborative writing of scientific manuscripts.
2	 Manubot is a tool for collaborative writing of scientific manuscripts. 		
3	 It utilizes version control and a continuous integration workflow to facilitate efficient and transparent collaboration among authors. 		
4	Manubot integrates with popular version control platforms such as GitHub, allowing authors to easily track changes and collaborate on writing in real time.	2	Manubot integrates with popular version control platforms such as GitHub, allowing authors to easily track changes and collaborate on writing in real time.
5	 Additionally, Manubot automates the process of generating a formatted manuscript (such as HTML, PDF, DOCX; Figure {@fig:ai_revision}a shows the HTML output), reducing the time and effort required for manuscript preparation and submission. 	3	+ Furthermore, Manubot automates the process of generating a formatted manuscript (such as HTML, PDF, DOCX; Figure {@fig:ai_revision}a].
6	Built on this modern and open paradigm, our AI-based revision software was built using GitHub Actions, which allows the user to easily trigger an automated revision task on the entire manuscript or specific sections of it.	4	Built on this modern and open paradigm, our AI-based revision software was built using GitHub Actions, which allows the user to easily trigger an automated revision task on the entire manuscript or specific sections of it.
		5	+ The AI-based revision task is based on a machine learning model trained on a corpus of scientific papers from the same field as the manuscript (Figure {@fig:ai_revision}b).
		7	+ This model is used to identify and suggest revisions to the text, resulting in a modified version of the manuscript that is ready for submission. + This reduces the time and effort required for
			manuscript preparation and submission.

Figure 8: A paragraph in the Methods section of ManubotAI. Original text is on the left and suggested revision on the right. The revision (right) contains a repeated set of sentences at the top that we removed to improve the clarity of the figure.

When revising the Methods sections of Manubot-AI (this manuscript), the model, in some cases, added novel sentences containing incorrect information. For example, for one paragraph, it included a formula (using the correct Manubot format) presumably to predict the cost of a revision run. In another paragraph (Figure §), it introduced new sentences stating that the model was "trained on a corpus of scientific papers from the same field as the manuscript" and that its suggested revisions resulted in a "modified version of the manuscript that is ready for submission". Although these are important future directions, neither statement accurately describes the present work.

Conclusions

Our tool, the Manubot AI Editor, integrates AI-based revision models into the Manubot publishing platform. Writing academic papers can be time-consuming and challenging to comprehend, so we aimed to use technology to assist researchers in communicating their findings more effectively. Our AI-based revision workflow uses a prompt generator that creates manuscript- and section-specific instructions for the language model. Authors can easily trigger this workflow from the GitHub repository to suggest revisions that can be reviewed later. This workflow utilizes GPT-3 models via the OpenAI API, generating a pull request of revisions for authors to review. We have established default parameters for GPT-3 models that perform well for our use cases across different sections and manuscripts. Users also have the option to customize the revision process by selecting specific sections, adjusting the model's behavior to suit their needs and budget, and even providing custom prompts instead of using the default, section-specific ones. This can be particularly beneficial for specific use cases that do not require a complex revision. Although evaluating automatic text revision is challenging, we found that most paragraphs were enhanced, while in some cases the model removed important information or introduced errors. The AI model also highlighted certain paragraphs that were difficult to revise, which could pose challenges for human readers as well.

We designed section-specific prompts to guide the revision of text using GPT-3. Surprisingly, in one Methods section, the model detected an error when referencing a symbol in an equation that had been overlooked by humans. However, revising abstracts proved more challenging for the model, as

revisions often removed background information about the research problem. There are opportunities to improve the Al-based revisions, such as further refining prompts using few-shot learning [16], or fine-tuning the model using an additional corpus of academic writing focused on particularly challenging sections. Fine-tuning using preprint-publication pairs [17] may help to identify sections or phrases likely to be changed during peer review. Our approach used GPT-3 to process each paragraph of the text, but it lacked a contextual thread between queries, which mainly affected the Results and Methods sections. Using chatbots that retain context could enable the revision of individual paragraphs while considering previously processed text. We plan to update our workflow to support this strategy. Open and semi-open models, such as BLOOM [18], Meta's Llama 2 [19], and Mistral 7B [20], are growing in popularity and capabilities, but they lack the user-friendly OpenAl API. We used a combination of human evaluation and automated tools available at the time to assess the outcomes of the Al-based revisions. Recent frameworks such as OpenAl Evals or strategies such as LLM-as-a-Judge [21] could be used to evaluate the quality of the revisions in a more automated way. Despite these limitations, we found that models captured the main ideas and generated a revision that often communicated the intended meaning more clearly and concisely. While our study used OpenAl's GPT-3, the Manubot Al Editor supports both GPT 3.5 Turbo and GPT-4 models, which were made available after the completion of our research.

The use of Al-assisted tools for scientific authoring is controversial [22,23]. Questions arise concerning the originality and ownership of texts generated by these models. For example, the *Nature* journal has established that any use of these models in scientific writing must be documented [24], and the International Conference on Machine Learning (ICML) has prohibited the submission of "papers that include text generated from a large-scale language model (LLM)" [25], although editing tools for grammar and spelling correction are allowed. Our work, however, focuses on revising existing text written by a human author. Additionally, all changes made by humans and AI are tracked in the version control system, which allows for full transparency. Despite the concerns, there are also significant opportunities. Our work lays the foundation for a future in which humans and machines construct academic manuscripts together. Scientific articles need to adhere to a certain style, which can make the writing time-consuming and require a significant amount of effort to think about how to communicate a result or finding that has already been obtained. As machines become increasingly capable of improving scholarly text, humans can focus more on what to communicate to others, rather than on how to write it. This could lead to a more equitable and productive future for research, where scientists are only limited by their ideas and ability to conduct experiments to uncover the underlying organizing principles of ourselves and our environment.

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