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Workflow for Extracting and Structuring Geolinguistic Data from Tesnière's Atlas

ABSTRACT

Tesnière's atlas, published in 1925 and translated into Slovene in 2022, is the first geolinguistic atlas of the Slavic languages as a whole. It represents a form of linguistic heritage that we aim to preserve and pass on to younger generations through digitisation. The atlas is currently available as a printed publication and as a static PDF. Our goal is to transform this static atlas into an interactive web-based resource that enables students and researchers to explore linguistic data dynamically through interactive maps, spatial visualisations, and advanced search. In addition, the digital version will support the integration and reuse of linguistic data across applications and research environments. This article presents the methodology and workflow used to digitise the atlas and prepare its linguistic and geospatial data for the future development of an interactive web atlas. Linguistic reflexes and information about maps and locations were manually transcribed, reviewed, and organised in a multi-sheet Excel workbook. Scanned maps were georeferenced in a GIS environment, and survey locations and linguistic areas were digitised as point and polygon features. The spatial data were exported as GeoJSON files and visually verified in a web environment before being aggregated with the tabular data, transformed, and validated using a custom Python processing pipeline. The resulting four interconnected datasets cover 65 digitised maps and contain 284 locations, 394 linguistic areas, and 6,329 reflexes. These datasets support visualisation, analysis, and reuse across different applications and research environments. Our future work will focus on their use in a fully functional interactive web atlas. However, the workflow presented here is not limited to Tesnière's atlas and can be applied to the digitisation of other historical linguistic atlases and similar cultural heritage collections.

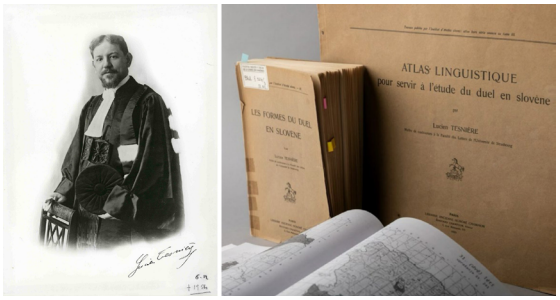
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KEY WORDS
Digitisation, linguistic atlas, GIS, georeferencing, cultural heritage

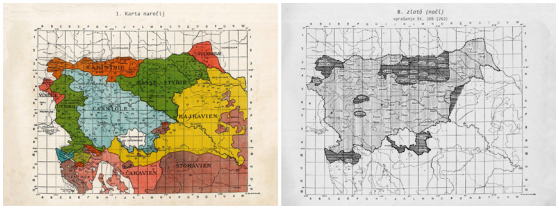
1. Introduction

Lucien Tesnière (1893–1956) was a French linguist who lived in Ljubljana from 1921 to 1924 and worked as a lecturer in French at the newly established University of Ljubljana (Figure 1, left). During this time, under the supervision of professor Antoine Meillet, he prepared his doctoral thesis on the dual in Slovene, which he defended in 1925. His work Les formes du duel en slovène (Tesnière, 1925a) constitutes the principal thesis, while the accompanying thesis was L'Atlas linguistique pour servir à l'étude du duel en slovène (Tesnière, 1925b). This linguistic atlas of the dual was compiled on the basis of a field questionnaire containing 425 questions, which local informants translated into their own dialects; Tesnière then wrote down the responses and entered them on to the maps. The atlas, in which examples of the dual are presented across dialects on individual maps, constitutes the first geolinguistic study of the Slavic languages. It was translated into Slovene only in 2022 (Tesnière, 2022), under the title Lingvistični atlas za študij dvojine v slovenščini (Figure 1, right).



» **Figure 1:** *Lucien Tesnière (left), Les formes du duel en slovène, l'Atlas linguistique pour servir à l'étude du duel en slovène and Lingvistični atlas za študij dvojine v slovenščini (right)*

The linguistic atlas (Tesnière, 1925b; Tesnière, 2022) comprises 70 maps. Each map is divided by meridians and parallels spaced at 10 arc-minute intervals. The rectangles delimited by this grid measure 18.5 km in length and have an average width of 13 km on the ground. These rectangles are numbered 1 to 13 vertically and labelled A to W horizontally. In the atlas, the maps themselves are numbered 1 to 70. The first map, entitled "Map of dialects" (Figure 2, left), shows the geographical division into individual regions, which also broadly indicate the dialect areas. This first map also includes 279 points representing localities – that is, locations where interviews were conducted with 88 speakers, or from which data were taken from existing dialectological literature. The names of these places are listed in two tables in the atlas. The following is a physical map of Slovenia, on the basis of which the other linguistic maps in the atlas were produced. It was prepared in 1921 at the Cartographic Institute in Paris (French: l'Institut cartographique de Paris) (Tesnière, 2022) and includes the names of certain mountain ranges and bays; it also uses the Greenwich prime meridian as its reference.



» **Figure 2:** *Map of dialects (left) and maps with phonetic transcriptions of dialect pronunciations (right)*

In addition to the maps already mentioned, the atlas also contains two stratigraphic cross-sections, while the other maps are two-dimensional and set within Slovene linguistic territory (Figure 2, right). As the author notes, on most maps colours had to be replaced, for typographical and above all financial reasons, by cartographic hatching (hachures), in which the nature and direction of the lines represent different colours, while the density of the hatching indicates different degrees of colour intensity.

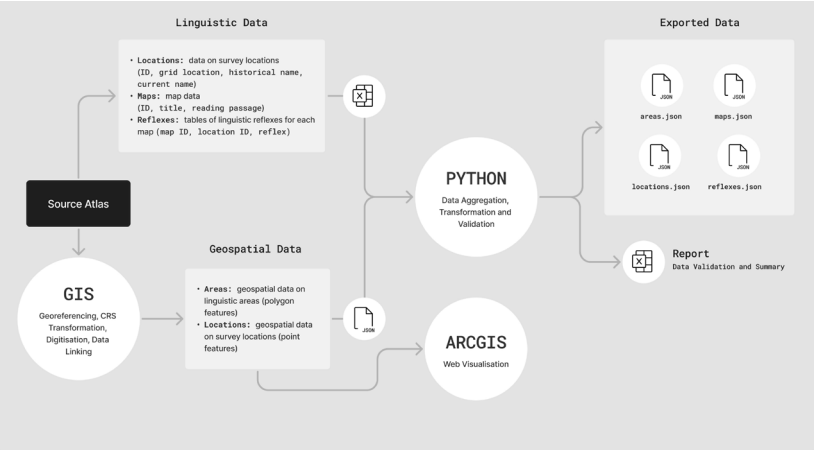
The digitisation of historical linguistic atlases is important not only for preserving their contents but also for making the underlying data more accessible and reusable. In the printed version, linguistic information remains closely tied to individual maps, limiting systematic retrieval, comparison and computational analysis. Converting the atlas into structured digital data helps preserve its information independently of the original physical publication and facilitates its visualisation, analysis, and reuse in linguistic research. Our long-term goal is to develop an interactive web version of Tesnière's linguistic atlas that will enable students and researchers to explore geolinguistic data through interactive maps, spatial visualisations, and advanced search.

The digital version will also enable the atlas to be supplemented with additional materials that could not be included in the printed edition, such as audio recordings. As a first step towards this objective, this article presents the methodology and workflow used to transform the static atlas content into structured geolinguistic data. It describes how information from the printed atlas was transcribed, how locations and linguistic areas were digitised, and how the resulting data were structured, linked, and validated. The prepared datasets provide a basis for their integration and reuse across different applications and for the future implementation of a fully functional interactive atlas.

2. Workflow for extracting and structuring geolinguistic data

The overall workflow is summarised in Figure 3. It consists of two digitisation streams. Linguistic reflexes and information about the corresponding maps and locations were transcribed and organised in tabular form, while survey locations and linguistic areas were digitised in a GIS environment. The resulting tabular and geospatial data are subsequently integrated, transformed, and validated to produce interconnected datasets suitable for web visualisation. The individual stages of this workflow are described in detail in the following subsections.

Of the 70 maps in the atlas, 65 were included in the digitisation process: 64 maps containing linguistic reflexes and map 1, which presents dialect areas. The remaining five contain other types of content: two stratigraphic cross-sections, two physical-geographical maps, and one map showing the extent of Yugoslavia (Tesnière, 2022).



» **Figure 3:** *Overview of the workflow for digitising and structuring geolinguistic data*

2.1. Digitisation of linguistic atlas data

As part of his research on the dual, Tesnière entered the reflexes obtained in interviews (i.e. the phonetic transcriptions of pronunciations) on the individual maps. The reflexes were transcribed with tonemic accentuation. Since the list of individual reflexes is not accessible (the manuscript is kept in the manuscript department of the National and University Library of Strasbourg, and the material is currently being digitised (Sušnik, 2005), it was necessary to transcribe the individual reflexes manually. For the purposes of digitisation, a list of the individual reflexes by locality was required so that they could be re-entered into the network of localities during the digitisation process, as every digitisation project necessarily involves a substantial amount of manual work.

We sought to simplify the transcription process in various ways, including the use of applications and artificial intelligence. However, because the reflexes are often written over the hachures, manual transcription proved more accurate. A further difficulty was the use of special symbols to mark tonemes. On the maps, the meridians and parallels form a degree grid, which made it possible to transcribe the reflexes more systematically.

The work was further facilitated by organising the data in a multi-sheet Excel workbook. The workbook contained two reference worksheets: one with data on locations, including the grid reference, location identifier, historical and current location names, and accompanying notes, and another with data on maps, including the map identifier and title, the relevant questionnaire number, and the associated Slovene text. A separate worksheet, based on a prepared template, was then created for transcribing the linguistic reflexes from each map. Once the map number and location identifier had been entered, the worksheet was partially populated automatically with the relevant data from the reference worksheets. The transcribed reflex and any accompanying notes were then added for each location (Figure 4). Following the initial transcription, the reflexes were reviewed by a second person and compared with the original maps.

An additional challenge was presented by the tonemic transcriptions of the reflexes, which were entered using the special ZRCola font. For this, we used the ZRCola input system provided by ZRC SAZU (ZRCola2, 2019), which enabled basic letter characters to be combined with more complex ones while typing. A further limitation was that the correct display of specialised characters encoded as Unicode Private Use Area code points depended on the availability of the ZRCola font. As described in Section 2.3, these characters were additionally converted into hexadecimal HTML numeric character references to make the underlying code points explicit and to facilitate data transfer and storage.



			Informacije o karti:	41	387–392	Mídva píševa, Mídva svà, Mídva vę̀va	
ZS točke (točka id)	Oznaka kvadrata	Ime kraja (tocka_kraj)	Kraj danes (tocka_kraj_nov)	Št. karte (karta_id)	Številka vprašanja	Slovensko besedilo* (besedilo_tekst)	Refleks
8	B3	Brdo	Brdo	41	387–392	Mídva píševa, Mídva svà, Mídva vę̀va	mądsȁ, mídva
11	E3	Malošče	Malošče	41	387–392	Mídva píševa, Mídva svà, Mídva vę̀va	mądsȁ
14	F3	Lele (Lesach, Lessach)	Lele	41	387–392	Mídva píševa, Mídva svà, Mídva vę̀va	(mídvà)
19	G3	Borovlje	Borovlje	41	387–392	Mídva píševa, Mídva svà, Mídva vę̀va	mbá (dva)
64	G4	Slovenski/Slovenji Plajberk	Slovènji Plájberk	41	387–392	Mídva píševa, Mídva svà, Mídva vę̀va	mídva
23	I3	Dobrla Ves	Dóbrla vàs	41	387–392	Mídva píševa, Mídva svà, Mídva vę̀va	nìba, oiba
68	I4	Železna Kapla	Želézna Kápla	41	387–392	Mídva píševa, Mídva svà, Mídva vę̀va	mędvȁ, vędvȁ
26	K3	Meja Podjunske doline (jaunthal)	Meja med Podjunsko in Mežiško	41	387–392	Mídva píševa, Mídva svà, Mídva vę̀va	mędva, mídva

» **Figure 4:** *Example of an Excel worksheet used to transcribe linguistic reflexes*

2.2. Georeferencing and spatial data digitisation

In this study, digitisation of geospatial data is used as an umbrella term for the conversion of scanned and later georeferenced cartographic material into vectorised layers with a structured set of attributes (Brennen & Kreiss, 2016). All steps of digitalisation were carried out in ESRI ArcGIS Pro 3.5 (ArcGIS Pro, 2025). The scans of the original maps were not produced within the project but were created for the 2022 translation of the atlas.

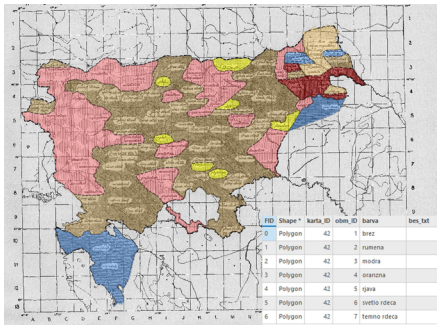
Before the individual maps were processed, two reference feature classes were prepared and used across the whole set of maps. The first was a point feature class containing 53 reference points corresponding to the intersections of the meridians and parallels of the graticule used by Tesnière, which is identical on all maps of the atlas and labelled in degrees and minutes. The points were not digitised from the scans but constructed from the known geographic coordinates of these intersections. The second was a polygon feature class defining the outer limits of the areas to be captured, that is, their maximum extent, together with the area of the German-speaking linguistic enclave of Kočevje (Gottschee), which is likewise identical on all maps. Rather than establishing control points and outer boundaries anew for each map, all operators worked from the same set of reference features. These two reference layers kept the georeferencing uniform across operators and maps, made the individual maps comparable and ensured that recurring areas were vectorised consistently throughout.

The scanned maps were imported as raster layers and georeferenced individually. The original cartographic projection could not be reliably reconstructed from the available material, as the atlas does not include any projection information beyond the graticule itself. The maps were therefore fitted to reference points derived from that graticule, and all work was carried out in the projected coordinate system WGS 84/Pseudo-Mercator (EPSG:3857). For each map, 53 pairs of control points were established, with the first point in each pair marking the position of a graticule intersection on the scanned map and the second the corresponding reference point. The transformation was computed from these pairs as a 2nd order polynomial, which allows a non-linear adjustment of the raster and is therefore suited to older scanned maps exhibiting minor geometric deviations, whether these originate in the initial cartographic production, in deformation of the paper, in uneven scanning, or in subsequent processing. The result of this stage was a georeferenced raster for each map, saved in TIFF format and serving as the basis for subsequent vectorisation (Figure 5).



» **Figure 5:** *Example of a georeferenced map with reference points*

For each map, a new polygon feature class was created to capture the areas of individual dialectal phenomena (Figure 6). The polygons representing the extent of the different dual forms of the word were drawn manually. All maps were vectorised at a uniform scale of 1:50,000, ensuring a comparable degree of generalisation across the set. The reference polygon feature class described above was used throughout as an aid in delimiting the outer boundaries and the Gottschee enclave, so that these recurring areas were captured consistently on every map. In addition to the areas, the locations at which Tesnière recorded his data were captured as a point feature class. The locations were identified from the first map and from the list of locations given in the atlas, yielding a total of 279 points, of which 250 lie within the present-day borders of Slovenia. Each point was placed at the centre of the corresponding present-day settlement. The result of this stage was, for each map included, a polygon feature class of the captured thematic areas together with a point feature class of places.



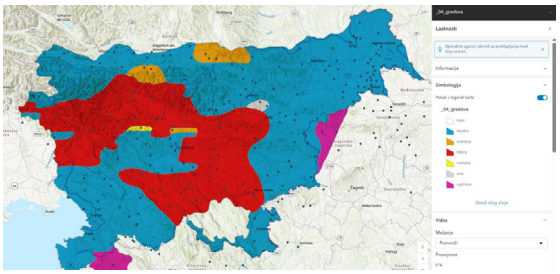
» **Figure 6:** *Digitised map and structured attribute table*

The attributes of the polygon feature classes were edited so that each captured area carried an identifier for the map to which it belonged, an identifier for the area itself, the colour category assigned to it on the original map, together with an empty field reserved for the word form. The point feature class of places was then joined to the polygons by means of a spatial join, which links a point layer to a polygon layer based on the spatial relationship

between them. Each location retained its locality identifier and name. The spatial join added the identifiers of the relevant map and containing area, the corresponding colour category, and an empty field reserved for the later entry of the pronunciation. For each digitised map, this process produced two GeoJSON files: a polygon file containing the geometries and attributes of the linguistic areas, and a point file containing the geometries and attributes of the localities. Point files were distinguished by the suffix _SJ, while the corresponding polygon files used the map filename without this suffix. Both types of files were reprojected to WGS 84 (EPSG:4326) during export, as required by the GeoJSON format specification. GeoJSON was chosen for its simple structure and wide support in web-based geographic information systems, which allows the spatial data to be used outside the software environment in which they were produced.

2.3. Web-based visual verification

After the spatial data had been exported from the GIS environment, the resulting GeoJSON files were visually verified in a web environment before data aggregation. The purpose of this step was to detect potential errors introduced during export and to identify locations or linguistic areas that might have been digitised incorrectly. ArcGIS Online was used for this purpose, and the entire verification was carried out using freely available functionality at no additional cost (Figure 7).



» **Figure 7:** *Example of a digitised map with localities in ArcGIS online web map viewer*

All exported GeoJSON files were imported directly, without any prior adjustment of the files, their attributes or their coordinate system. For each original map, two layers were imported: a point layer of the settlements and a polygon layer of the areas of pronunciation. The layers were assembled into a single web map in Map Viewer. The polygons were symbolised with unique values based on the colour attribute, separately for each map, and the maps were viewed individually by manually switching the visibility of the corresponding pair of layers on and off.

The rendering of the layers and their spatial position were inspected visually, and the attributes and attribute structure were reviewed. The exported locations and linguistic areas were compared with the original maps to verify that they had been transferred correctly and that the spatial features had been digitised accurately. The settlement points were also compared with their associated polygons to verify that each point fell within the area assigned to it. This visual verification made it possible to identify potential export errors, incorrectly positioned locations, and incorrectly drawn area boundaries before the data were aggregated and transformed.

2.4. Data aggregation, transformation and validation

After digitising the linguistic and geospatial data, the resulting datasets were aggregated, transformed, and validated using a custom data-processing pipeline implemented in Python. The pipeline was designed to integrate different types of data: tabular data stored in a multi-sheet Excel workbook and geospatial data exported from the GIS environment as GeoJSON files. During processing, these separate data sources were transformed into a data model suitable for subsequent use in a web environment. The main steps of the data-processing pipeline are summarised in Algorithm 1 and described in detail below. The resulting model is presented in Section 3.1.

Algorithm 1: Data processing pipeline

```
INPUT:
    Tabular data (maps, locations, and reflexes)
    Geospatial point data
    Geospatial area data

IDENTIFY required fields
READ maps, locations, and reflexes
CLEAN values and NORMALISE identifiers
SKIP incomplete location and map records
SKIP duplicate map records

FOR EACH point feature:
    VALIDATE and NORMALISE identifiers
    ASSIGN point geometry to location
    COMPARE with previously assigned geometry
    RECORD geometry conflict, if detected
    IDENTIFY area association, if available

FOR EACH polygon feature:
    VALIDATE and NORMALISE identifiers
    CREATE area with composite identifier
    EXTRACT polygon geometry
    LINK locations to area
    RECORD duplicate area, if detected

CHECK for area associations without polygon geometry
RECORD missing area geometries

FOR EACH reflex record:
    VALIDATE required identifiers
    RECORD invalid row and SKIP it, if necessary
    ASSIGN map and location identifiers
    IDENTIFY associated area, if available
    RECORD missing area association or geometry
    CREATE unique reflex identifier
    ENCODE PUA characters

CHECK for locations without point geometry
AGGREGATE recorded validation results
EXPORT maps, locations, areas, and reflexes
GENERATE report
```

The tabular data input consists of a multi-sheet Excel workbook containing data on locations, maps, and linguistic reflexes, as described in Section 2.1. Because the relevant information is stored in multiple worksheets with varying structures, the required fields are first identified in each worksheet by their column headers. During import, leading and trailing whitespace is removed from textual values, and identifiers are normalised to support

consistent linking between the tabular and geospatial data. Location records are skipped if they lack an identifier or both location names, while map records are skipped if they lack an identifier or both the title and accompanying text. Duplicate map records are also excluded.

The geospatial input consists of point features representing survey locations and polygon features representing linguistic areas. Processing of the geospatial data begins with the point features, which are first validated and normalised. Point geometry is assigned to the relevant location, and the associated area is determined when the necessary identifiers are available. Where the same location occurs in multiple geospatial files, its geometry is compared with the geometry already assigned to that location. If the geometries differ, the previously assigned geometry is retained and the conflict is recorded.

The polygon features are then processed to create the corresponding linguistic area records, with the map and polygon identifiers first validated and normalised. Since polygon identifiers are unique only within an individual map, each area is assigned a composite identifier combining the map identifier and the polygon identifier. For example, polygon 3 on map 4 results in the composite area identifier "4_3". The polygon geometry is extracted from each feature, and the locations associated with the corresponding composite identifier are linked to the area. Duplicate area identifiers are recorded as soon as they are detected. Once all polygon features have been processed, the pipeline checks whether any area associations derived from the point data lack a corresponding polygon feature and records the affected areas and locations.

The process then iterates through the reflex records. For each record, the required map and location identifiers are first normalised and validated. Records lacking either identifier are classified as invalid, recorded with their worksheet and row number, and excluded from the output. Each valid record is assigned a unique identifier and retains the relevant map and location identifiers from the source data. If the location is associated with an area on the relevant map, the area's composite identifier is assigned to the reflex record.

Missing area associations and associations without a corresponding polygon feature are also documented. Since reflexes may contain non-standard phonetic characters represented by Unicode Private Use Area (PUA) code points in the ZRCola font, their correct display depends on the availability of this font. To ensure compatibility, PUA characters are also converted to hexadecimal HTML numeric character references. This preserves the original transcription while providing an alternative form suitable for data transfer and storage.

After the point, polygon, and reflex processing stages, the pipeline additionally identifies locations without point geometry and aggregates the recorded validation results. Where available, relevant source information, such as the worksheet and row number or the GeoJSON file, is retained to enable problematic records to be traced back to the source data.

Finally, the processed data are exported as four interconnected datasets representing maps, locations, linguistic areas, and linguistic reflexes. The pipeline also generates a single Excel report containing an overall data summary, processing statistics, source information, and detailed validation results. The summary provides the overall numbers of maps, locations, areas, and reflexes, together with indicators of data completeness and consistency.

3. Results and discussion

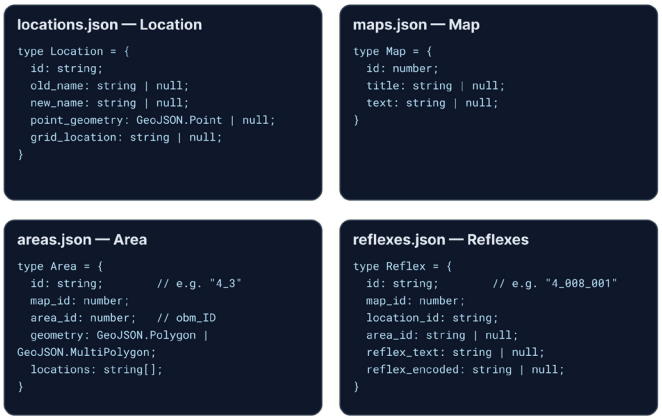
3.1. Data model and dataset structure

The final data model consists of four main entities: maps, locations, linguistic areas, and linguistic reflexes (Figure 8). Maps and locations contain information shared across multiple records, while areas and reflexes are linked to them through the identifiers described in Section 2.4. A map can include multiple areas and reflexes, while the same location can appear on multiple maps. Each reflex is linked to a map and a location, and, where an area association is available, to the relevant linguistic area. This structure reflects the organisation of the original atlas while avoiding the repetition of map and location data in individual reflex records.

Separating the four entities enables independent querying and updating while preserving their relationships. It also supports the intended features of the interactive atlas, including displaying locations and areas, retrieving reflexes for a selected location or map, and comparing linguistic phenomena across maps.

3.2. Dataset overview and validation results

The final datasets cover 65 digitised maps and contain 284 locations, 394 linguistic areas, and 6,329 reflexes. Validation identified no missing point or polygon geometries and no invalid reflex records lacking the required map or location identifiers. However, some linguistic areas had no associated locations despite containing survey points. Inspection in the GIS environment revealed that overlaps between certain polygons had caused locations to be automatically assigned to incorrect areas. These errors were corrected, and the data were re-exported and checked again. This illustrates the



» **Figure 8:** *The final data model*

iterative nature of the workflow, in which results are reviewed and, where necessary, corrected and verified.

The web-based test proved advantageous in several respects, while at the same time revealing the limitations of the environment in which it was carried out. The exported files were imported without any intervention in the data, so that the test also served as a check on the export itself. It was carried out on a web platform, in an environment corresponding to the intended use of the data, where shortcomings in encoding, projection or attribute handling that a desktop environment tolerates become more apparent. Displaying the layers together, moreover, allowed the spatial consistency of the points and polygons to be examined visually, which cannot be judged from the attribute table alone. Several limitations were identified as well. Each layer took a considerable time to load whenever it was made visible, which made moving through the set of maps slow; switching between maps was entirely manual, as the environment provides no mechanism for turning one pair of layers off when another is turned on; the phonetic transcriptions could not be displayed in the custom font that is indispensable here, as the environment does not permit custom fonts to be added. The whole process – loading, symbolising and inspecting each layer in turn – was carried out manually, which, at 130 layers, made the check possible but time-consuming. Taken together, these limitations indicate that a web map of this kind is not suitable for public release, and that the atlas will require a purpose-built solution in which the shortcomings identified here can be overcome.

4. Conclusions

The article outlines the methodology and workflow used to digitise Tesnière's linguistic atlas and prepare its linguistic and geospatial data for further use. Linguistic reflexes and information about maps and locations were transcribed and organised in tabular form, while survey locations and linguistic areas were georeferenced and digitised in a GIS environment. The exported geospatial data were visually verified in a web environment, then aggregated with linguistic data to produce four interconnected datasets. The resulting datasets support visualisation, analysis, and reuse in linguistic research across different environments, independently of the platform, technology, or programming language used.

Our future work will focus on using the resulting datasets to develop a fully functional interactive web atlas that supports displaying locations and areas, retrieving reflexes for a selected location or map, comparing linguistic phenomena across maps, and adding supplementary materials such as audio recordings.

5. Acknowledgments

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