

Exploring Students' Map Decoding Processes Using Eye-Tracking

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Abstract

Research on map skills in geography education and beyond looks back on a considerable tradition. Using different methods, previous studies have dedicated special attention to the specific skill of map decoding, diagnosing various challenges primarily related to symbolic and geometric decoding. This paper uses the Map Skills Model by Hemmer et al. (2010) to provide additional insight into students' map decoding skills. Eye-tracking was used to explore students' actions during map decoding task processing. The results of this exploratory study offer, on the one hand, further empirical evidence regarding the validity of the map decoding skills defined in the Map Skills Model. On the other hand, the findings show practitioners what (un)successful map decoders do while decoding symbols and the map's geometry. The paper also discusses various avenues to improve the methods applied, and the sampling for future studies.

Key words: geography education, map reading, spatial cognition, eye-tracking, post-primary school, secondary school

Introduction

Maps have historically constituted both the most fascinating and the most dreaded part of Geography as a school subject. While all map types seem challenging, thematic maps pose a particular challenge for learners. This is a surprising finding, given the central role of maps in geography education and the considerable number of teaching and learning aids that support students and teachers alike in developing map skills. Research in geography education and beyond has addressed several facets of map skills. Still, the particularities of the challenges

students encounter during task processing remain underexplored.

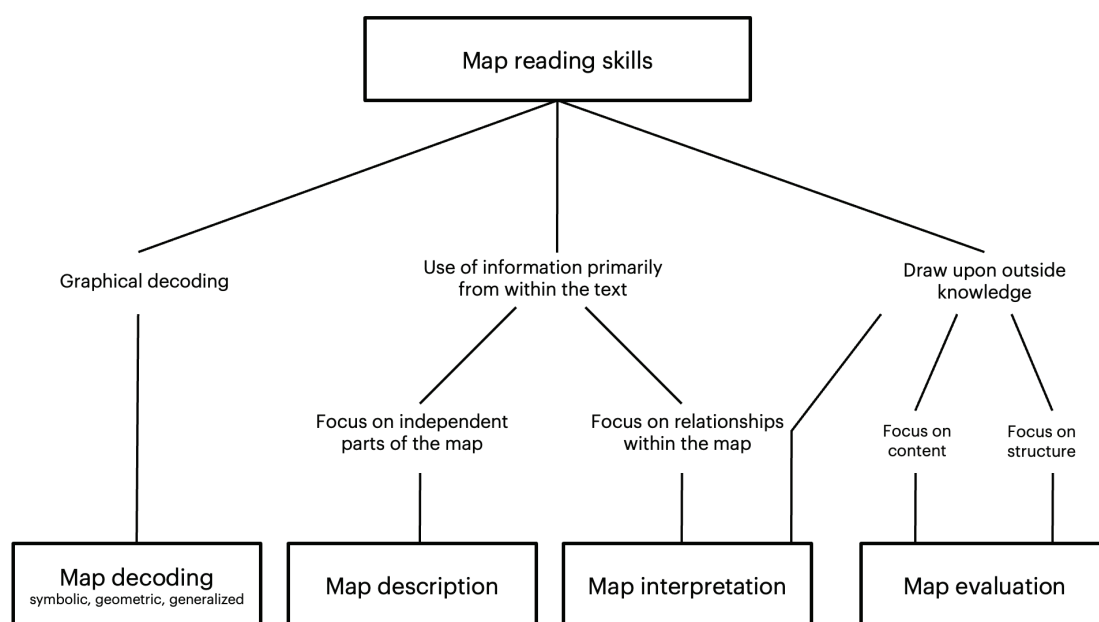
Therefore, this paper aims to shed light on student strategies for map decoding using eye-tracking. Following a brief overview of map decoding, the third section describes the research methods and sample used in this study. The subsequent fourth section introduces the main findings. Following the discussion in the fifth section, the paper concludes with some concluding remarks.

Map Decoding

In formal education, several school subjects address students' spatial intelligence; however, given their educational aims, their contributions are heterogeneous. For example, arts or physical education contribute only to a limited extent, while geometry and Geography traditionally make the most significant contribution. Geography, in particular, focuses on both spatial orientation and map skills. Previous studies both explored, to some extent empirically, various facets of map skills and spatial orientation and offered practical guidance for the teaching and learning of Geography. Such praxeological literature often includes aspects of geography lesson preparation, delivery, and (skill) assessment. An Australian example for primary education is the compendium by Catling et al. (2013).

Despite its diversity, research in geography education, as Hüttermann (2007) argues, has made several significant contributions to a better understanding of how map skill acquisition takes place. One crucial contribution is emphasising the key difference between continuous and discontinuous text. In students' daily learning experience, continuous text refers to the linearly

Figure 1: Map Skill Model (Bagoly-Simó & Hemmer, 2012, p. 295, adapted)



structured written text of a novel or the text featured on the pages of the geography textbook. In contrast, discontinuous text refers to non-textual elements, such as pictures, graphs, drawings, cartoons, or maps—all of which are structured non-linearly. Inherently, some discontinuous text may entail, at least in parts, continuous text. Such integrated formats, one of which is maps, are particularly challenging to navigate.

The fundamental difference between reading a text and a map lies in the guidance they provide to the reader. While continuous texts require a specific direction (in English, starting at the left top of the page and proceeding to the right, repeating this pattern row by row), most discontinuous text types are free from such restrictions. For example, reading a picture or a map has neither a specific starting point nor a given direction to follow systematically. For map readers, this translates into the freedom of either meticulously reviewing the title, legend, scale, and orientation, focusing on specific content details, or opting for another strategy.

Despite these differences, discontinuous and continuous texts pose similar cognitive challenges for readers, as both require knowledge of the codes. What letters, words, and sentences are to the continuous text, symbols, colours, and scale are to the map. Consequently, reading the pages of a novel and the content of a map retain a certain similarity. Therefore, Hemmer et al. (2010) used the PISA Model of Reading Literacy (Baumert et al., 2001) as the foundation of their Map Skills Model (cf. Figure 1); however, as maps combine continuous text with visual information, they further considered the Integrated Text-Image-

Understanding Model by Schnotz & Bannert (1999, 2003).

The Map Skills Model (Hemmer et al., 2010) entails three skills with map reading constituting its core. Reading a map starts with learning to *decode* its symbols, geometry, and generalisation. In the second step, readers first focus on specific parts of the map (*map description*; e.g., settlements, rivers, mountains) and later explore relationships among the several specific elements (*map interpretation*; e.g., relations between resources, industry, settlements). In a third step, readers are required to draw on information beyond the given map, such as pictures, graphs, texts, or even other maps. The final step, *map evaluation*, requires readers to assess both the content and the structure of the map—a fundamental skill for every critical citizen.

Decoding in the Map Skills Models encompasses symbols, geometry, and generalisation. Scholarly interest in these three forms of decoding has been continuous but heterogeneous, as evidenced by the empirical studies and conceptual works of the last six decades.

Cartographic symbols constitute one of the most significant challenges for less experienced map readers. Over the decades, studies (cf. Bartz, 1965; Catling, 2018, 2020; Elg, 2003; Gerber, 1984; Monmonier, 1996; Sandford, 1979; Wiegand, 2002) using various research designs repeatedly confirmed that learners, in general, and less experienced ones, in particular, struggle with symbolic transformation (i.e., decoding the meaning of map symbols).

Another challenge arises from the map's geometry. Geometric decoding refers to the map

reader's ability to navigate distances on maps. There is rich evidence, presented over decades, indicating that students struggle when using the scale (bars) (e.g., Bartz, 1971; Boardman, 1988; Gerber, 1981; Towler & Nelson, 1968), have difficulties in understanding depth and height (cf. Boardman, 1983; Dove et al., 1999; Harwood & Jackson, 1993; Livni & Bar, 1998), often fail to correctly process contour lines (e.g., Boardman, 1988; Liben & Downs, 1989), or struggle to align their maps using cardinal points during navigation and wayfinding (cf. Boardman & Towner, 1979; Hemmer et al., 2007).

While equally important, generalisation, the third form of map decoding, received only modest scholarly attention. Despite their limited number, these studies delivered evidence that both secondary (e.g., Battenfield & McMaster, 1991; Sandford, 1981) and tertiary education students (Herzig et al., 2007) encountered difficulties in understanding generalisation while working with thematic maps, for example, in geomorphology.

When contextualised within the broader scholarship on map skills, Bagoly-Simó et al. (2025) identified three main fields that also address map decoding. A first set of studies worked on how educational resources, in general, and textbooks, in particular, (progressively) introduced map skills. Given the prevalence of content analysis as the preferred research method, most studies examined the links between cartographic content and map skill acquisition. The main merit of studies focusing on educational resources was, on the one hand, uncovering the lack of progression across grades. On the other hand, limited progression is often paired with inconsistent skill consolidation and application within the individual and across several grades.

A second set of studies used eye-tracking to better understand student behaviour during map work. While they used eye-tracking for data collection, the studies explored quite different facets of map skills, such as the impact of map design on user behaviour, map readers' information selection strategies, and map skill testing using map-like prototypes.

Finally, a third strand of research on map skills connects eye-tracking to additional physiological data, such as brain activity and cardiovascular data. Such methodological innovation addresses some of the shortcomings of studies that rely solely on eye-tracking.

Within this rich and diverse research tradition on map skills, this explorative study seeks to contribute to the debate on map decoding by focusing on what students do during task processing using eye-tracking. This paper primarily aims to showcase, on the one hand,

how eye-tracking can contribute to a better understanding of student behaviour during map decoding. On the other hand, its objective is to clearly indicate the limitations of this method.

Method & Sample

This study used eye-tracking to collect data on the strategies students employed while solving map decoding tasks. Participants wore a portable eye tracker while observing stimuli on a laptop screen.

Research with children, in general, and eye-tracking studies, in particular, require familiarity with both the hardware used and the data-generation process. Therefore, each student worked with an initial exercise and had the opportunity to ask clarifying questions. A welcome slide announced the test's commencement and repeated what the student was expected to do. Each of the subsequent five slides contained a stimulus consisting of the task and a thematic map of Australia (cf. Figure 2).

Eye-tracking studies generally use constructed stimuli (prototypes; cf. Bagoly-Simó et al., 2025) rather than original cartographic representations used in geography classrooms. The present study addresses this shortcoming by using stimuli originating from a German school atlas. As data collection took place in Hungary, after translation into Hungarian, geography teachers cross-checked the translation's accuracy and the map's suitability for the study, including age appropriateness. The stimulus was a map of Australia with some deviations from standard cartographic representation. For example, symbols normally used to indicate urban settlements by size represented the number of Aboriginal Australians.

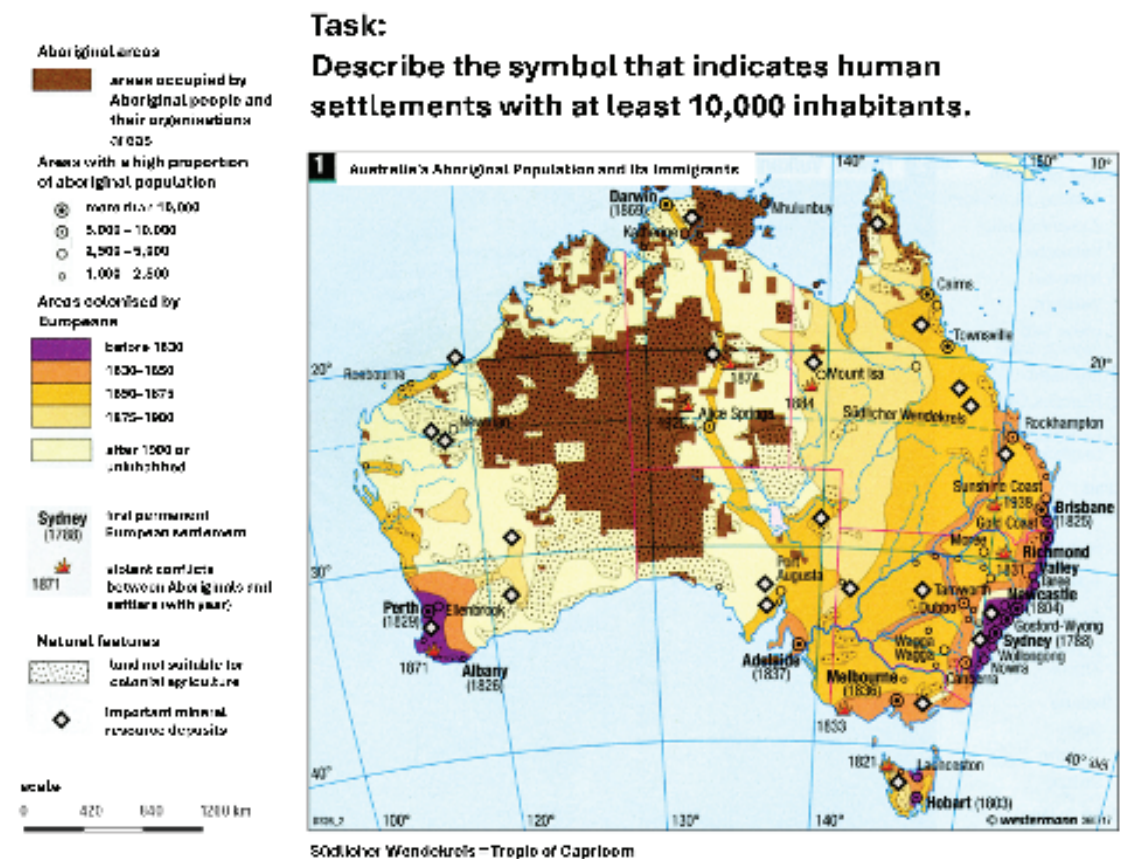
The five slides contained the stimulus and the following tasks:

- T1: Which symbol represents settlements with an Aboriginal Australian population of at least 10,000 individuals?
- T2: How does the map represent the process of European colonisation?
- T3: How many Aboriginal Australians live in Sydney?
- T4: Determine the shortest distance (straight line) between Perth and Sydney.
- T5: Determine the shortest distance (straight line) between Melbourne and Darwin.

Concerning decoding skills, T1–T3 target symbolic decoding, while T4 and T5 refer to geometric decoding.

Data analysis began with timestamp processing to determine task processing duration. The second

Figure 2: Stimulus used during data collection for T1



step aimed to determine the eye movement trajectory, which is why close observation of each video was required. Two independent coders processed the two videos and compared their respective sequences. A total of four mismatches required revisiting the video for final clarification.

Following ethics clearance, two geography teachers facilitated access to seventh-graders (ages 13–14). Hungarian formal education prescribes Geography as a mandatory subject in grades 7–10, which is why the sampling considered the initial year of geographic education. Over the first six years of schooling, geographical content is included in interdisciplinary subjects, while upper secondary geography is an elective subject.

The study took place in the Hungarian city of Szeged. Student participation was voluntary, and the study had no effect on teachers' overall assessment of the students' performance. The teachers provided additional information on each student, particularly concerning their achievements in Geography.

Given its exploratory nature, the sample for this paper consisted of only two seventh-grade students: student 7S, who successfully completed the map decoding tasks, and student 7L, who was less successful on the specific tasks of this study. Unlike the main study, the

aim of this paper is merely to visualise student strategies during successful and less successful processing of the map decoding task, with the aim of offering teachers and practitioners insights into what studies employing eye-tracking can add to their existing diagnostic tools. As the aim is to show both successful and less successful strategies, the selection of the two case studies was independent of overall school achievement, preference for Geography, or any other indicators provided by students or their teachers. The selection focused solely on the first year of formal geography education and on students' specific performance during map decoding at the time of data collection.

Results

Three indicators seem particularly useful for describing student behaviour during map decoding. *Processing time per task* provides quantitative information on the time required to process each task, *while eye movement trajectories* during task processing visualise the specific path of eye movement. *Strategy* refers to the relevance of information consulted while solving the task. Previous studies validated all three indicators (Bagoly-Simó et al., 2025).

The subsequent subsections introduce the main findings based on these three indicators, focusing first on basic decoding skills and proceeding to

their application to specific map content. Table 1 summarises the main findings.

Checking the Basics

The first two tasks (T1 and T2) targeted map symbols (see section 3). Students could correctly solve the task by consulting the legend, which contained all the required information. In contrast, neither the title nor the content of the map was relevant to T1 and T2.

The results are threefold. First, concerning *time*, both students required 69 seconds to process T1 and T2 (cf. Table 1). At the beginning, 7S required almost twice as much time to process T1 as 7L. Concurrently, the processing time from T1 to T2 dropped by 43 per cent for 7S and increased by 36 per cent for 7L.

Second, the *eye movement trajectory* (cf. Table 1) shows a similar overall pattern, with 7S exhibiting two longer trajectories and greater repetition of short sequences than 7L. In addition, there is an overall decrease in sequence length from T1 to T2, namely by 41 per cent for 7S and 14 per cent for 7L. In addition, both students repeatedly devoted visual attention to the map—an element generally not required by the two tasks that inquired about legend content. The expected pattern includes looking at the task and the legend.

Finally, there are clear differences between the two students' *strategies*. For T1, 7S spent considerable time on both relevant (task and legend) and irrelevant map elements (map content). However, the recording revealed that 7S first identified the correct symbol and then

spent the remaining time checking its accuracy by contrasting it with the map content eight additional times. This pattern remained consistent for T2, though with a dramatically decreased processing time and sequence. Overall, 7S found the correct answer in the shortest time but spent considerable time testing their solution by contrasting the symbol with the map. In contrast, 7L displayed a consistently inconsistent pattern while processing both tasks. While working on T1, 7L only once glanced at the map content, spending most of their time alternating between the task and the legend, aimlessly scanning both elements without success. For T2, the student adopted a different strategy: reading the task only once and spending considerably more time oscillating between the map content and the legend, with most of that time spent scanning the map content. For both tasks, 7L repeatedly scanned the correct region of legend but failed to identify the correct information, assigning meaning to specific cartographic symbols.

Applying the Basics

The remaining three tasks (T3–T5) added map content to the information required to solve them.

For T3, in an ideal solution, students could locate Sydney and match the symbol with the legend to determine the number of Aboriginal Australians living in the city. Alternatively, they could first consult the legend for the symbol used for cities with an Aboriginal Australian population of at least 10,000, and cross-check it against the symbol used for Sydney on the map. Regarding *time*, 7S took 60 per cent longer to process the task than 7L (cf. Table 1). The *eye movement*

Table 1. Expert and novice students' map decoding (processing duration and eye movement trajectory)

Task	Student	Processing time (in sec)	Eye movement trajectory
T1	7L	27	TCLTLTL
	7S	44	TCLCLTCTCLCLCTLCTLCLCL
T2	7L	42	TLCLC
	7S	25	TCLTCLCLT
T3	7L	31	TCLT
	7S	48	TCTLCLCLTLCLCLCLCTLC
T4	7L	58	TCLCLCLC
	7S	34	TCLCLCLCLCT
T5	7L	4	TCLC
	7S	22	TCLCLCLC

T=task; C=map content; L=legend

trajectory recorded for 7S is five times longer and entailed several repetitive elements. Within specific *strategies*, 7S correctly identified both the correct symbol in the legend and Sydney on the map; however, they oscillated seven times between the legend and the map, including the task on three occasions, before communicating their response to the researchers. Thus, for 7S, the significantly longer processing time translated into confirmatory circles. In contrast, 7L spent most of their time scanning the map content, briefly glancing at the legend, and then returning to the task.

Moving away from symbolic decoding, T4 and T5 required students to use their geometric decoding skills to determine distance. Both tasks tested the same skill and required students to coordinate information provided in the task, on the map, and in the legend (linear scale). Consequently, the ideal solution entailed the identification of the scale in the legend, locating the cities on the map, and using the scale to determine the distance between them (straight line).

Based on the results in Table 1, it is important to first consider only T4 before comparing the two similar tasks. Regarding T4, 7S needed 41 per cent *less time and an eye movement trajectory* that was 27 per cent longer to process the task than 7L; however, both students repeated the eye movement string of map content-legend (CL) several times. The strategies used by both students were similar, albeit they led to different results. Both 7S and 7L started the task and oscillated between the map content and the legend several times, with 7S taking an iteration longer and ending with a final glance at the task. However, the recording showed significant differences: 7S proceeded according to the prototypical solution, even using their hand as an aid to better measure the distance. In contrast, 7L identified the scale but failed to identify the cities and apply it to measure the distance between them.

The last task (T5) used two different cities but required the students to apply the same geometric decoding skill. The results show that both students became aware of this fact, leading to faster task processing (by a third) by 7S and an almost instant abandonment by 7L (cf. Table 1). Both students repeated the *eye movement trajectory* described for T4 and also maintained the repetitive eye movement strings (cf. Table 1). Concerning *strategy*, 7L abandoned the task, but only after having consulted the legend and the map content. In contrast, 7S applied the same strategy as described for T4, including using their hand as an additional aid for distance measurement. For 7S, the main differences lie

in the shorter overall processing time and the abandonment of final cross-checking.

Discussion

Decoding Strategies

Both teachers and educational media designers are equally interested in providing better support to students in developing their spatial thinking skills. In Geography, this primarily translates into map skills. While traditional assessment measures skills based on individual or group outcome, eye-tracking visualises the process leading to (un)successful task processing. Therefore, eye-tracking studies have the potential to assist educators in developing more effective teaching and learning environments for map skill acquisition and development.

The first essential aspect that eye-tracking data *visually* demonstrate is that students apply strategies when decoding maps. In diagnostic terms, unlike thinking aloud (contributing to cognitive load) or post-test reconstructive methods, eye-tracking depicts the task-solving process and, inherently, shows student strategies. Therefore, the large-scale study conducted in Hungary aims to develop a typology of student strategies based on eye-tracking data, ultimately equipping teachers with more effective diagnostic tools. Ideally, eye-tracking data can help teachers provide personalised support to students struggling with map skills.

Task processing *time* is the second important aspect that is better understood based on eye-tracking data. Based on the findings of this exploratory study, there is a complex link between map decoding proficiency and task processing time. Despite the prototype answers being rather simple, successful students may take a similar amount of time to process map decoding tasks as their less successful counterparts. One case study alone revealed several confirmatory iterations that tend to decrease with task familiarity (see T4–T5). For teachers, the two case studies presented here show that processing time alone seems less suitable as a sole diagnostic tool.

In more generic terms, and as the third central aspect, this paper contributes to further validating the Map Skills Model (Hemmer et al., 2010) by confirming the map decoding skills. Eye-tracking data show that symbolic and geometric decoding constitute two separate and essential skills, and successful students apply clear strategies when using them to solve tasks.

Finally, when decoding maps, students seem to adapt their strategies according to the situation. Rather than always applying the same prototypical strategy rooted in decades of teachers'

praxeological knowledge, successful students seem to weigh factors, such as familiarity with map content, task formulation, and assessment stakes when processing map decoding tasks. There is a strong likelihood of a correlation between processing time and task-solving strategy.

Overall, the results of this study entail the promise of a better understanding of students' map decoding. Nonetheless, a range of questions arises that, in some cases, requires a critical evaluation of the study's many limitations.

Methodological Development

It is fundamental to stress that this paper aimed only to show, using two examples, how eye-tracking of original cartographic material from an atlas can serve as an improved diagnostic tool. Therefore, a range of limitations and questions need to be addressed.

Regarding data collection, a wider variety of thematic and physical maps should be used to test map decoding skills. As the results show, maps derived from educational resources used in the teaching and learning of Geography are a suitable and preferred stimulus compared to artificially-constructed stimuli (Bagoly-Simó et al., 2025).

Task structure and quality also play an important role. For example, T2 directly invited students to also look at map content by asking "how does the map represent" a specific content, even though the legend alone could have provided the necessary information to correctly solve the task.

The eye-tracking data may offer a better understanding of how the two students processed the map decoding task; however, additional methods, for example including other physiological data, are required to better explain this complex process (Bagoly-Simó et al., 2025). As outlined above, visual data alone fail to explain why students make the choices in specific learning and assessment situations. Therefore, post-test interviews based on recorded eye movements could shed further light on the test person's motivation, insecurities, and decision-making during task processing. Similarly, alternative strategies that rely on the same skills, often in a different order, could be explored using the post-test interview format.

Conclusions

This paper aimed to offer a different insight into student strategies for map decoding using eye-tracking. The results showed how students applied their skills and uncovered patterns and strategies of varying length. However, recording

eye movements and the verbal solutions to the tasks only partially explain the complex process of map decoding. Further methods, such as post-test video-based interviews and additional physiological data, seem reasonable for an improved understanding of map decoding skill development and application. Therefore, future studies should further develop the method mix, extend the sample, and consider the other map skills represented in the Map Skills Model (Hemmer et al., 2010), aiming to provide educators with improved diagnostic tools and educational media producers with better guidelines to better meet student needs.

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