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REVIEW ARTICLE

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Gaze controlled maps: scoping review of gaze-based interactions in geovisualisations

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ABSTRACT

Gaze-based interactions (GBIs) allow hands-free control and richer user experiences across domains. Yet, despite eye-tracking's diagnostic use in geospatial visualisations, its potential for interactive spatial data exploration is underexplored. By providing a scoping review of the integration of GBIs into geospatial visualisations, we aim to lay the foundation for further research, as no comprehensive review has yet been carried out.

Using the PRISMA-ScR framework, we assessed 26 studies employing 54 GBIs. We developed an open-source web dashboard to simplify the interpretation of multiple data items across GBIs. Most GBIs (74.1%) relied solely on gaze, with 68.5% using remote eye-trackers. Active interactions dominated (64.2%), primarily for discrete commands concerning zooming, panning, or selecting map elements. Meanwhile, passive interactions focused on gaze-informed adaptations, such as automatically updating legend content based on in-map attention. Although there were accuracy and unintended activation issues, GBIs often improved the hedonic and pragmatic quality of geovisualisations.

Studies would benefit from robust user evaluations that use standardised questionnaires. Broader GBI research solutions, such as combining gaze with other modalities in extended reality, could transform how we interact with geospatial data.

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KEYWORDS
Gaze-based interaction; human–computer interaction; cartography; geovisualisation; eye-tracking

1. Introduction

Since the 1980s, gaze-based interactions (GBIs) have enabled individuals with severe motor impairments to communicate and control interfaces through eye movements (Hamid and Kristensson 2024). Recent advances in eye-tracking have enabled GBIs to expand into diverse domains – including enhancing immersion in virtual reality, improving productivity in human–computer interaction, and adapting educational settings to maintain an appropriate level of challenge (Duchowski et al. 2018; Esteves et al. 2015; Hou et al. 2023). In cartography, however, gaze remains underused as an input modality

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(Keskin and Kettunen 2023), with most studies employing eye-tracking diagnostically – analysing gaze patterns post hoc to study attention and inform design (Kiefer et al. 2017; Ooms et al. 2012; Popelka, Burian, and Beitlova 2022).

Interactivity plays a central role in modern cartography. As Crampton (2002) explains, the concept of geovisualisation emerged in response to the increasing complexity of spatial data, reflecting a need for dynamic, exploratory, and interactive mapping environments. Rather than passively viewing static maps, geovisualisation enables interaction across four core dimensions: with data, its representation, temporality, and contextualisation. These interactions have long been supported primarily by traditional input modalities – such as mouse, keyboard, and touch – while gaze remains notably underutilised.

GBIs offer an emerging hands-free modality for interacting with cartographic systems, potentially reducing cognitive load and physical effort. While gaze can support familiar tasks such as zooming, filtering, and linking data layers, its reliance on implicit attention enables novel interactions in which geovisualisations may appear to anticipate user intent and respond seamlessly (Keskin and Kettunen 2023; Vojtechovska 2024). However, rather than replacing existing modalities, gaze should extend the interactive repertoire available to cartographers, in line with Crampton's view on interactivity. Just as touch interfaces have transitioned from novelty to ubiquity, gaze input may follow a similar trajectory as eye-tracking becomes more accessible.

This scoping review synthesises how GBIs have been employed in cartographic systems, characterising interactive use cases, identifying research gaps, and outlining directions for future gaze-enhanced geovisualisation.

1.1. Gaze-based interactions

The potential of GBIs in cartography can be first assessed by examining their successful use in other fields. Whether remote, head-mounted, or webcam-based, eye-tracking systems capture real-time data, including point-of-gaze, pupil dilation, and eye movement patterns. These include fixations (when the eyes remain focused on a single point), saccades (quick ballistic movements of eyes), and smooth pursuits (where the eyes follow a moving object), among others (Majaranta et al. 2019).

Computer systems can process this real-time eye-tracking data into individual GBIs, offering rapid, intuitive interaction with digital interfaces. Often, a system integrates multiple GBIs for added flexibility. Such interactions provide distinct advantages over conventional methods such as computer mouse and keyboard, including hands-free control, reduced physical effort, and the capacity to reflect or infer the user's intentions and cognitive load (Majaranta et al. 2019; Mulvey and Heubner 2014; Ohno and Hammoud 2008).

GBIs can be categorised in several ways, such as by input modality (upper part of Figure 1). Interactions can rely solely on gaze or they can be part of a multimodal approach that integrates gaze with inputs such as touch and voice (Majaranta et al. 2019). Extending Duchowski's (2018) work, our second type of categorisation is by the intent-response divide, recognising GBIs as either (1) active, where users directly control the interface, or (2) passive, where the system adapts its behaviour and visuals based on the user's gaze patterns. These categories have further subcategories (bottom part of Figure 1).

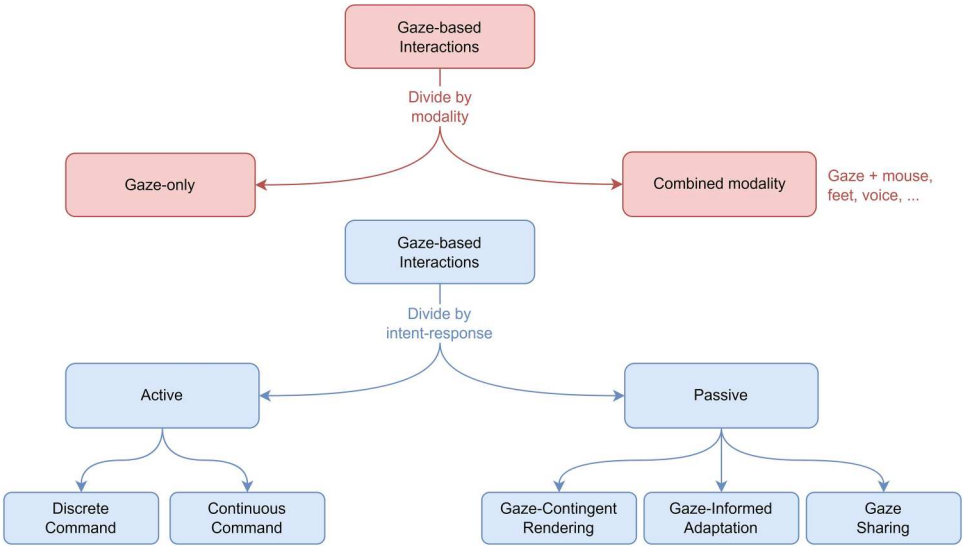

Figure 1. Types of users' GBIs for digital interface manipulation.

Active GBIs, also called explicit (Kiefer et al. 2017; Majaranta et al. 2019), involve direct control by the user, where systems interpret eye movements as intentional commands to manipulate the interface or select objects. We further categorise them into:

- **Discrete Commands** allow users to intentionally use gaze to trigger a specific response in a system, such as selecting an item or issuing a command. Individuals with motor impairments use these commands to navigate computer interfaces or eye-typing (Hamid and Kristensson 2024). For non-disabled users, they allow hands-free selection of objects in public kiosks, museum displays, and more (Vidal, Bulling, and Gellersen 2013). In virtual environments, these selections offer better task completion times than hand gestures (Wagner et al. 2023).
- **Continuous Commands** interpret ongoing gaze data as a fluid input stream, allowing dynamic, real-time control based on where and how the user looks. For instance, the Dasher interface (Ward, Blackwell, and MacKay 2000) uses continuous gaze to input text by steering toward letters in a zooming interface, enabling users to write words without selecting each character individually for higher speed. Beyond assistive use, it can enhance navigation in complex environments, as Pavan Kumar et al. (2020) demonstrated by continuously adjusting the camera view from an unmanned aerial vehicle to an operator's gaze.

Passive GBIs, also called implicit (Kiefer et al. 2017; Majaranta et al. 2019), involve systems that monitor the user's gaze but do not use it for direct control. Instead, the interface dynamically adapts to the user's attention, gaze behaviour, or cognitive state (Ohno and Hammoud 2008). We categorise them into three subtypes:

- **Gaze-contingent rendering**, or foveated rendering, responds directly to the user's point-of-gaze, dynamically adjusting the interface within the user's foveal and

peripheral areas. Systems often implement foveated rendering to save computational resources, rendering high-resolution content only at the user's point-of-gaze; a feature found in many modern extended reality (XR) devices (Wang, Shi, and Liu 2023). In addition, this approach enhances comfort in virtual 3D spaces by improving depth perception and reducing motion sickness (Terzioğlu, Celikcan, and Capin 2024). Additionally, obscuring peripheral details can influence gaze patterns. For example, this could help slower readers to read faster (Albert, Godinez, and Luebke 2019).

- **Gaze-Informed Adaptation** interprets the user's gaze patterns to infer higher-level contexts such as attention, cognitive load, and needs, and adapts the application's behaviour accordingly. For instance, AI-driven personal assistants can analyse gaze data to identify objects of interest and provide real-time advice (Konrad et al. 2024). In educational platforms, systems adapt task difficulty dynamically by gauging the student's cognitive load (Duchowski et al. 2018). Additionally, in designing tasks, the system can analyse gaze to suggest images similar to those the user focused on, reducing the need for manual exploration (Lee et al. 2023).
- **Gaze Sharing** visually renders the user's gaze without changing the content or behaviour of the application itself. In educational settings, real-time gaze sharing between instructors and learners has improved learning outcomes, particularly for low-achieving students. It allows instructors to track their cognitive states better and provide more accurate feedback (Sung, Feng, and Schneider 2021). In XR collaborations, gaze visualisations enhance co-presence and mutual understanding (Jing et al. 2022). Similarly, in physical-world tasks, systems that visualise a colleague's gaze – often as a torchlight-like beam – simplify object referencing and instruction following (Akkil et al. 2016).

1.2. Rationale and objectives for scoping review

GBIs have been successfully applied across domains, supporting interactions from hands-free control to adaptive responses driven by user gaze. Yet, in cartography, their use remains limited. This may stem from challenges such as imprecision and unintended selections, identified in broader GBI research (Majaranta et al. 2019) and potentially amplified in map-based contexts. While prior reviews have explored eye-tracking in spatial research (Kiefer et al. 2017) and its potential for interactive geovisual exploration aided by machine learning (Keskin and Kettunen 2023), neither provided a focused, systematic assessment of GBIs in cartography – underscoring the need for their holistic evaluations.

Such evaluations are crucial, aligning with the ISO/IEC 9241-11 definition of usability, which emphasises effectiveness, efficiency, and user satisfaction in specific contexts (International Organization for Standardization 2018). In cartography, these aspects are essential for ensuring that geovisualisation tools are not only functional but also intuitive and accessible to diverse users. Cognitive research has long been recognised as fundamental in cartography, as reflected in the research agenda proposed by MacEachren and Kraak (2001) and later refined within the International Cartographic Association (Virrantaus, Fairbairn, and Kraak 2009). The focus on usability – spanning user-centered design, cognitive challenges, and geovisual perception – demonstrates that understanding user interaction is not just beneficial but necessary for optimising geovisualisation

tools. A systematic evaluation of GBI usability could, therefore, provide valuable insights into improving the effectiveness and user experience of cartographic applications.

The scoping review consolidates fragmented research on cartographic GBIs, focusing on how GBIs enhance user experience in various modes of interactions with geovisualisations. The review explores common interaction modalities, benefits, challenges, and possible gaps, structuring the effort around the following research questions (RQs):

- **RQ1:** How are GBIs applied in cartographic tasks?
- **RQ2:** Which modalities and eye movement types do cartographic GBIs utilise?
- **RQ3:** What are the documented benefits of GBIs in cartographic interfaces?
- **RQ4:** What challenges are associated with implementing cartographic GBIs?
- **RQ5:** What gaps exist in the current research on cartographic GBIs?

2. Methods

A scoping review systematically maps existing knowledge to clarify concepts, identify gaps, and assess the scope of evidence – particularly useful in emerging fields. To ensure methodological transparency, reporting consistency, and systematic coverage of the literature, we adhered to the PRISMA-ScR guidelines (Tricco et al. 2018), a structured checklist designed for scoping reviews. The review protocol contains further details on methodology, including specific search queries for articles in indexed databases (see Supplementary Materials). Due to the uncharted nature of the topic, we created the protocol after three initial iterations of search query refinements with a general understanding of the contents of eligible articles without pre-registration.

After filtering out duplications, we included articles that met the following **inclusion criteria**: The article is a research or proceedings paper, including early access. Second, it must be in English. Finally, the study simultaneously practically implements a passive or active GBI, as defined in the Introduction, and includes direct interaction with maps or other geospatial visualisations. We did not restrict the publication year to ensure a comprehensive literature review.

As **information sources**, we utilised several comprehensive databases that index a broad spectrum of scientific literature as our primary information sources, namely Web of Science, Scopus, and ACM Digital Library, along with a snowballing technique to identify additional relevant articles. We excluded Google Scholar because its results vary across users and lack reproducibility – making it unsuitable for systematic retrieval.

We designed the **search strategy** to identify articles that fit the inclusion criteria while minimising false positives. We divided the search terms into cartography and GBIs categories, with the final set refined through three iterations. Each iteration involved screening article titles and abstracts to evaluate and adjust the search terms. In the third iteration, we opted for individual search terms instead of compound ones to reduce complexity and improve precision. Keywords within the same category were combined using OR, while those in more than one category were combined using AND. The final queries, adapted for each database, are available in the Supplementary Material, and the overall workflow is depicted in Figure 2.

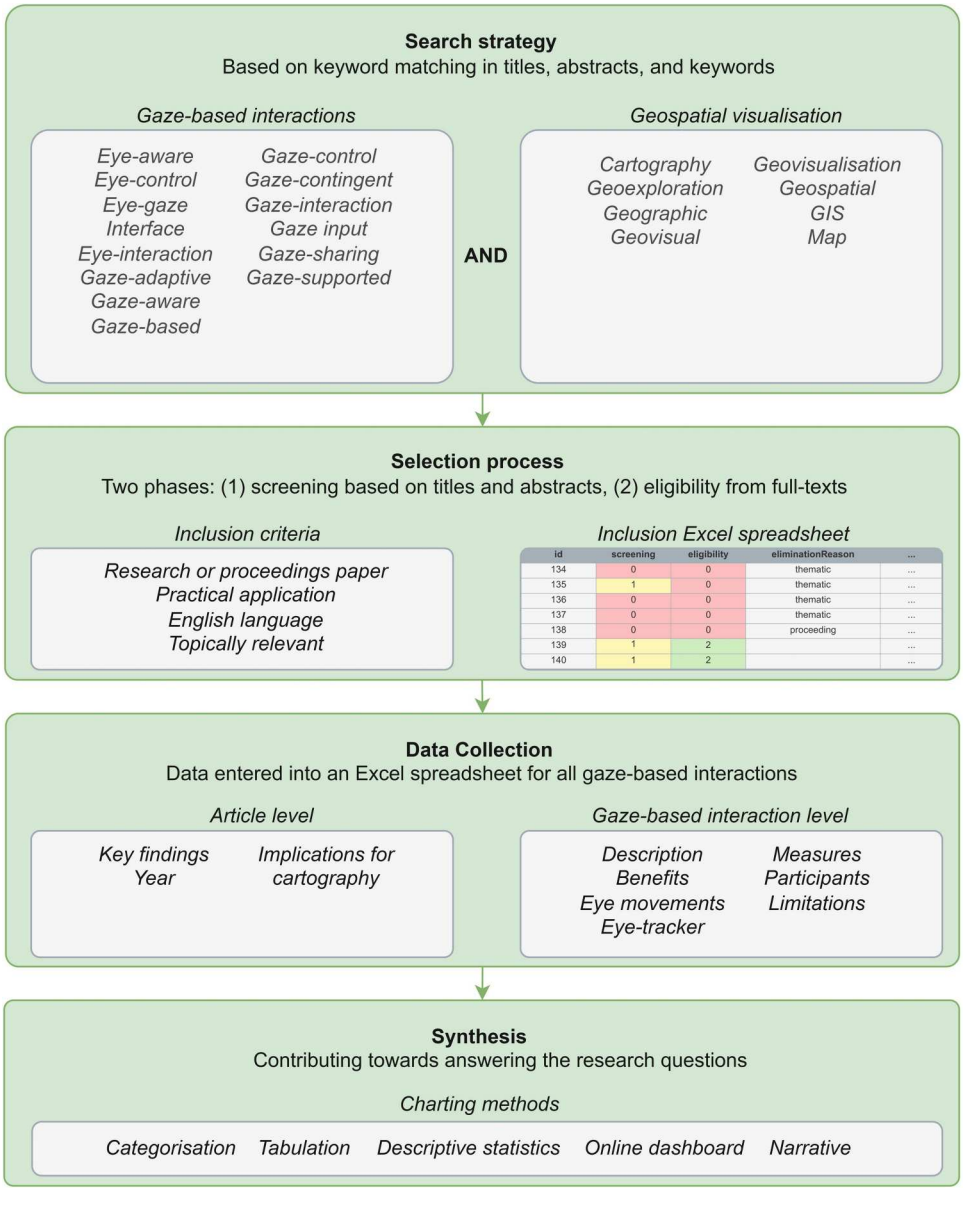

Figure 2. The scoping review methodology workflow.

The **selection process** was performed by one researcher in two stages. After initial screening based on titles and abstracts, full-text eligibility checks followed. Articles not meeting the inclusion criteria were excluded at each stage. The process was tracked in a Python-generated Excel spreadsheet, which recorded article details and review stages, omitting journal and author information to minimise bias. The spreadsheet is included in the supplementary material for cross-checking.

We collected **data items** at the article and task levels, as one system can involve multiple GBIs. At the article level, this included study type, key findings, and implications for cartography. At the task level, data included task descriptions, benefits, eye movement

types, the eye-tracker used, category membership (modality and intent-response divide), outcome measures, and limitations. Each data item was carefully defined, and fully described in the review protocol.

To facilitate **data collection**, full texts were manually reviewed using Zotero, first highlighting relevant text passages, and later populating an Excel spreadsheet with all data items. We also utilised Google's Notebook LM, a large language model, to assist with specific articles by locating exact text passages for verification. The researcher carefully cross-checked all claims made.

To answer RQs, the data was then processed using several **charting methods**. First, eye-tracking technologies were categorised by system type and then grouped based on interactions with geospatial visualisations, each contextualised simultaneously within modality and intent-response divides. Descriptive statistics, including frequencies and percentages, highlighted patterns in GBI characteristics, system types, and interaction styles. To support meaningful conclusions and provide quick orientation in individual GBIs, we developed an interactive, open-source dashboard using Svelte and TypeScript. Finally, a narrative synthesis summarised the findings of cartographic GBI groups and RQs, identifying themes, challenges, and broader implications.

3. Results

3.1. Selection of sources

Figure 3 details the scoping review selection process. From 335 records identified across Web of Science, Scopus, ACM, and two snowballed records, 120 duplicates were removed. Screening 215 records led to the exclusion of 171 due to thematic mismatches and other conflicts. After assessing 46 full-text articles, 20 were excluded, resulting in 26 studies being used in the final review.

3.2. Characteristics of sources

Figure 4 shows a growing trend in research activity after the first study in 2002. From the 26 sources, we identified 54 GBIs, with most (74.1%, 40 out of 54) relying solely on gaze as the input modality. This pattern is even more pronounced in passive GBIs, where nearly 95% use only gaze. In contrast, the remaining GBIs incorporate additional modalities alongside gaze. Of these 14 combined modality interactions, 42.9% (6) involve foot-based input, 28.6% (4) utilise touch, with one case also including device tilt, 21.4% (3) incorporate mouse input, and 7.1% (1) integrate head movement.

When categorising the 54 GBIs by the intent-response divide, 34 were identified as active, interpreting gaze as intentional commands. Of these, the majority (76.5%, 26) involved discrete commands, while 23.5% (8) supported continuous commands. The remaining 19 GBIs were classified as passive, where the system responds to gaze without explicit user input. Within 20 interactions in this passive category, 30.0% (6) involve gaze-contingent rendering, 65.0% (13) enable gaze-informed adaptations, and 5.0% (1) focus on gaze sharing.

Of the 54 GBIs, most GBIs (68.5%, 37) utilise remote eye-tracking, with head-mounted devices present in 25.9% (14). A few alternative methods, such as eye-tracking

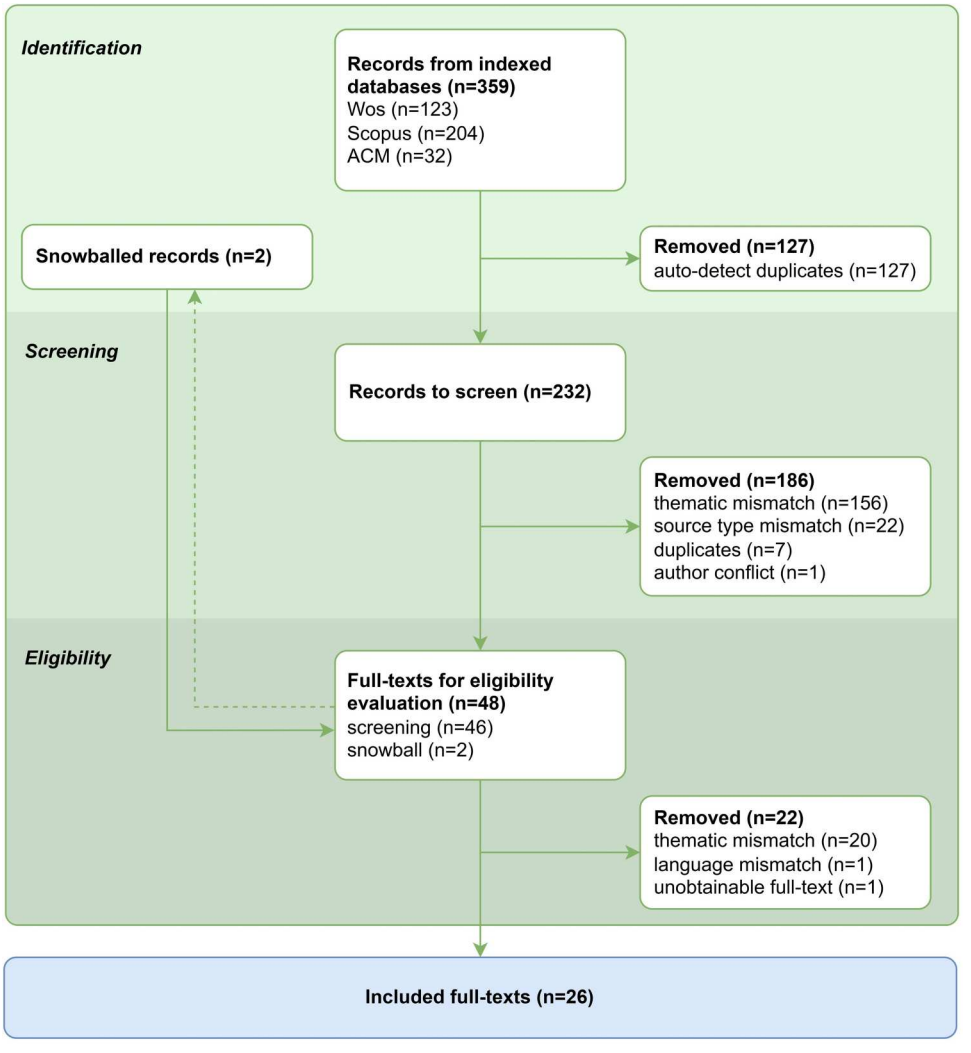

Figure 3. Selection process of the scoping review.

integrated into XR, inferred from gyroscope data, and a mouse-based system for concept testing, are used.

3.3. Results of individual sources of evidence

Benefits, limitations, and the potential for each of the 54 GBIs can be explored interactively in great detail through a web presentation accessible at https://carto-gbi-review.netlify.app/. GBIs are categorised by cartographic task groups according to modality and the intent-response divide, as shown in Figure 5. Each group is summarised below.

3.3.1. Active, discrete command, gaze-only

- **Gaze-Only Dwell Activation** (n = 10) allows users to control map functions such as zooming and panning by focusing on buttons or specific screen areas using a

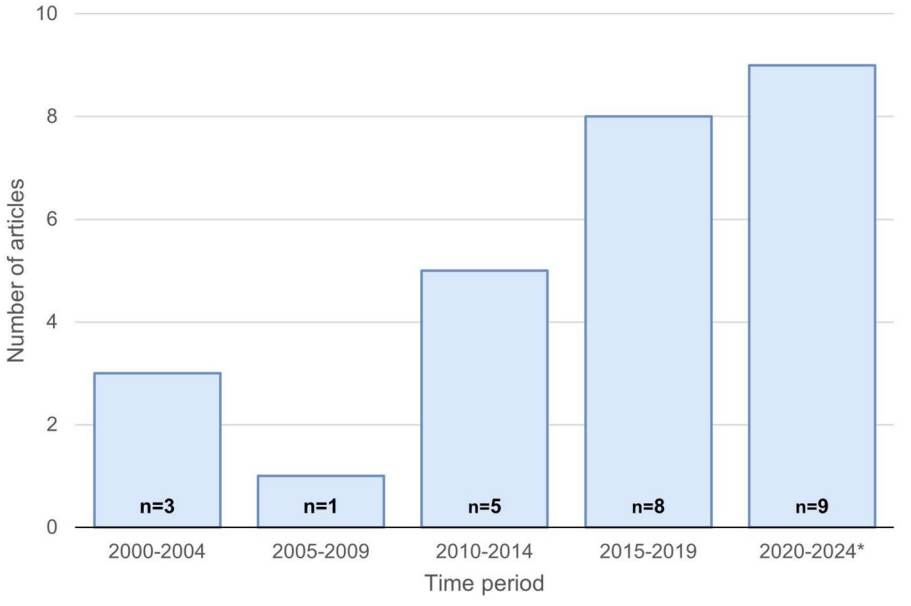

Figure 4. Temporal distribution of gaze-enhanced geovisualisations studies (*data up to September 2024).

dwell-time threshold (Gepner, Simonin, and Carbonell 2007; Zhang et al. 2022). While this is promising for accessibility and hands-free scenarios, such as XR settings, it struggles with unintended activations, tracking inaccuracy, and user fatigue.

- **Gaze-Only Dwell Feature Selection** (n = 4) involves selecting specific map features, such as points or polygons, through gaze interaction and dwell-time thresholds (Eaddy et al. 2004; Zhang, Liao, and Meng 2024). Challenges include tracker inaccuracies and the risk of unintended selections. Besides the hands-free benefit, it may also outperform mouse input in complex tasks.
- **Blink-Only Gesturing** (n = 3) employs blinking as a gesture to trigger commands to a cartographic interface, bypassing gaze-point reliance (Putra and Ogata 2022). While useful for low-precision eye-trackers, it suffers from unintended activations, user fatigue, and command conflicts, requiring more testing and refinement.
- **Gaze-Only Minimap Navigation** (n = 1) pans a main map view by directing the gaze to a specific point in an adjacent minimap (Gepner, Simonin, and Carbonell 2007). Though faster than hand gestures for large screen navigation, it is slowed down by dwell-time thresholds in the specific implementation, and prolonged use may lead to fatigue.

3.3.2. Active, discrete command, combined modality

- **Gaze-Pivot Central Zooming** (n = 7) uses gaze as an anchor for all-screen zooming, while another modality, such as feet, touch, or mouse, controls the zoom level (Çöltekin et al. 2016; Klamka et al. 2015). While improving engagement and sense of speed, overly complex controls can make coordination difficult, affecting overall task performance and satisfaction.

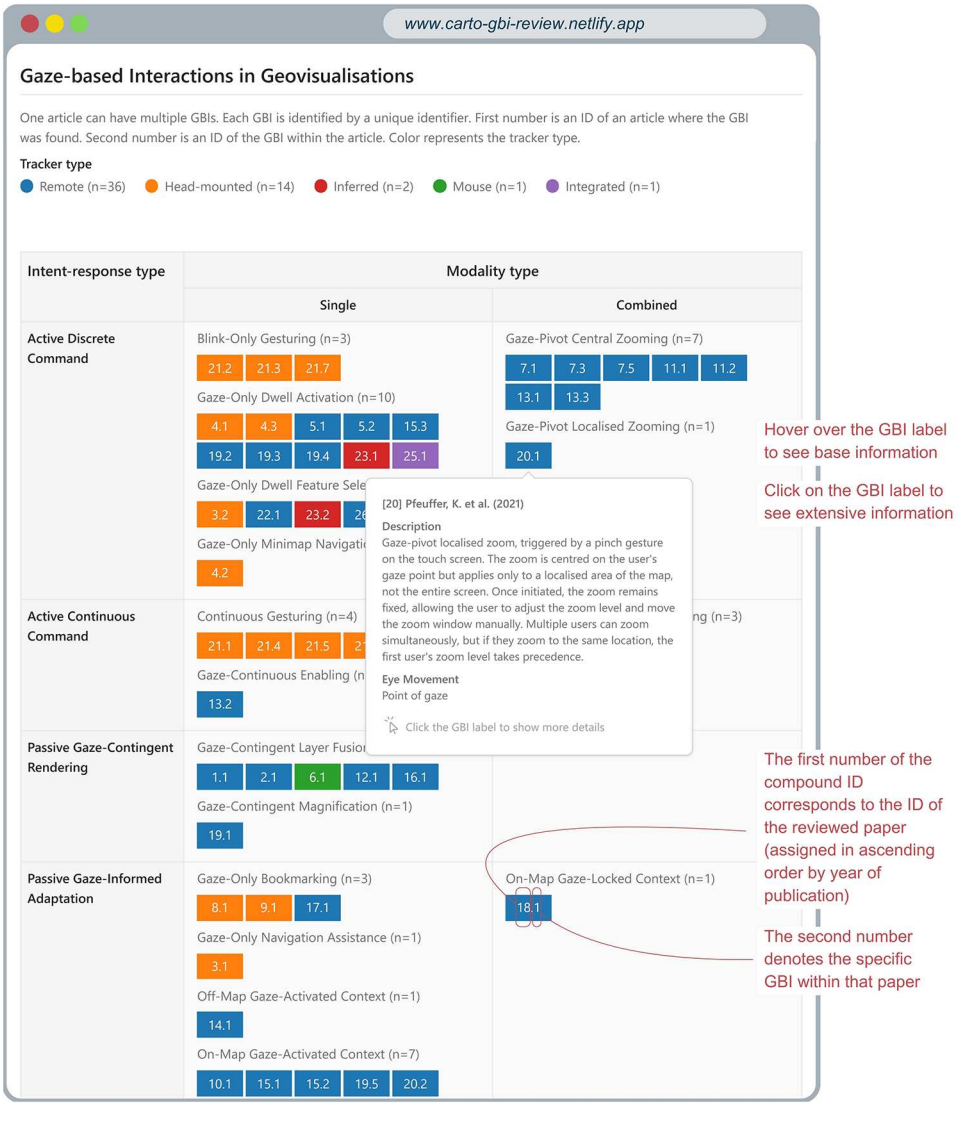

Figure 5. Interactive overview of GBIs in geovisualisations.

- **Gaze-Pivot Localised Zooming** (n = 1) centres the localised zoom window on the user's gaze, while being triggered or further controlled by another modality, such as touch. It allows multiple users to zoom in on a shared map without interference, but calibration and inaccuracy challenges were noted (Pfeuffer, Alexander, and Gellersen 2021).

3.3.3. Active, continuous command, gaze-only

- **Gaze-Only Joystick Gesturing** (n = 4) simulates joystick controls using gaze direction for tasks such as panning and zooming, and it functions well with a lower-accuracy eye-tracker (Putra and Ogata 2022). However, users faced issues of slow performance,

difficulty maintaining control, and head fatigue, highlighting the need for further testing.

- **Gaze-Continuous Enabling** (n = 1) activates interactions based on gaze location, such as enabling panning when looking at map edges (Çöltekin et al. 2016). However, this design led to serious collisions with the natural gaze flow, resulting in slow response times and frustration.

3.3.4. Active, continuous command, combined modality

- **Gaze-Directed Continuous Panning** (n = 3) uses gaze for continuously determining panning direction, while another modality, such as mouse, touch, or feet enables movement and controls speed (Klamka et al. 2015; Stellmach and Dachselt 2012). While it is intuitive for small adjustments, rapid panning may cause motion sickness and is less effective for larger movements. Users reported high engagement, though some modalities had challenges such as unintended activations and slower learning curves.

3.3.5. Passive, gaze-contingent rendering, gaze-Only

- **Gaze-Contingent Layer Fusion** (n = 5) adjusts map layers based on gaze, displaying high-resolution details where the user looks, while peripheral areas are simplified (Bektaş et al. 2019; Nikolov et al. 2002). This helps to reduce visual clutter and optimises navigation or target detection, but challenges include noticeable transitions, eye-tracker sensitivity, and flickering.
- **Gaze-Contingent Magnification** (n = 1) creates a magnified region around the user's gaze, improving information clarity and pragmatic and hedonic interface quality (Xie et al. 2021). However, it faced challenges due to inaccuracies and will require further testing.

3.3.6. Passive, gaze-informed adaptation, gaze-only

- **On-Map Gaze-Activated Context** (n = 7) adapts to provide users with additional information when they are focusing on specific map content. Legends can highlight the relevant symbology (Göbel et al. 2018), and maps can activate new in-map contexts (Pfeuffer, Alexander, and Gellersen 2021). It increases engagement and potentially reduces task times, though it can face challenges; tracking inaccuracies, information overload, visual fatigue, and a subjective feeling of lacking control.
- **Off-Map Gaze-Activated Context** (n = 1) updates the map based on the user's gaze on non-map content, such as text, linking it to relevant locations (Tateosian et al. 2017). While this enhances reading experiences and integrates geographic information smoothly – making it suitable for applications such as story maps and intelligence reports – frequent updates can be distracting.
- **Gaze-Only Bookmarking** (n = 3) helps users revisit points of interest by showing their gaze history, speeding up map searches, and improving orientation (Giannopoulos, Kiefer, and Raubal 2012; Göbel and Kiefer 2019). However, untoggleable markers can distract users, and further testing in varied contexts would be beneficial.
- **Gaze-Only Navigation Assistance** (n = 1) uses gaze tracking to steer users through maps with audio or visual prompts (Eaddy et al. 2004). Tested on public static map

kiosks, the GBI was faster than using a street index. However, it suffers from imprecise tracking.

3.3.7. Passive, gaze-informed adaptation, combined modality

- **On-Map Gaze-Locked Context** (n = 1) lets users access and lock contextual information using gaze and a secondary modality. In Goebel et al. (2020), users navigated a heatmap and locked the focus window with a mouse click, improving target location and recall. However, participants reported occasional lags and jitters, while the authors suggested a comparison with traditional map views.

3.3.8. Passive, gaze-sharing, gaze-only

- **Gaze Point Only Sharing** (n = 1) renders users' points of gaze in real-time, allowing better collaborative interaction. However, user testing is limited, and practical effectiveness remains uncertain, as stated in a proof-of-concept by Pfeuffer, Zhang, and Gellersen (2015).

Recurring observations of benefits and limits across all groups are shown in Figure 6.

3.4. Synthesis of results

3.4.1. RQ1: how are GBIs applied in cartographic tasks?

From the perspective of Crampton's (2002) geovisualisation interaction framework, all four high-level interaction types – interacting with data, data representation, temporality, and contextualisation – were represented across the reviewed GBIs. Approximately two-thirds of cartographic GBIs were active, issuing commands or selecting features based on intentional eye movements. However, passive GBIs adapting the interface to gaze patterns were the first to be recorded. In 2002, gaze-contingent rendering was used to optimise map detail in a user's focal area (Nikolov et al. 2002), though it did not yet generate interest in passive GBIs within cartography. A few subsequent studies introduced dwell-based active discrete command GBIs for selecting map features and controlling the map view (Gepner, Simonin, and Carbonell 2007) – most likely the most straightforward way to integrate gaze into map interactions. These early efforts were led by computer scientists using maps as a demonstration platform for the technology.

In the 2010s, the use of GBIs in cartography began to diversify and grow, with cartographers exploring additional ways to create gaze-enhanced map interfaces. Notably, gaze history allowed users to visualise where they had previously focused, aiding in orientation tasks (Giannopoulos, Kiefer, and Raubal 2012; Göbel and Kiefer 2019). Concurrently, computer scientists continued to provide technological demos, showcasing such innovations as gaze sharing for enhanced user awareness in collaborative tasks, and on-map context adaptations that automatically revealed details during joint interactions on large displays. The on-map context adaptations evolved further with cartographer-driven advancements such as gaze-adaptive legends, which helped with the use of complex thematic maps by highlighting the map symbols users fixated on (Göbel et al. 2018). Meanwhile, Tateosian et al. (2017) demonstrated off-map

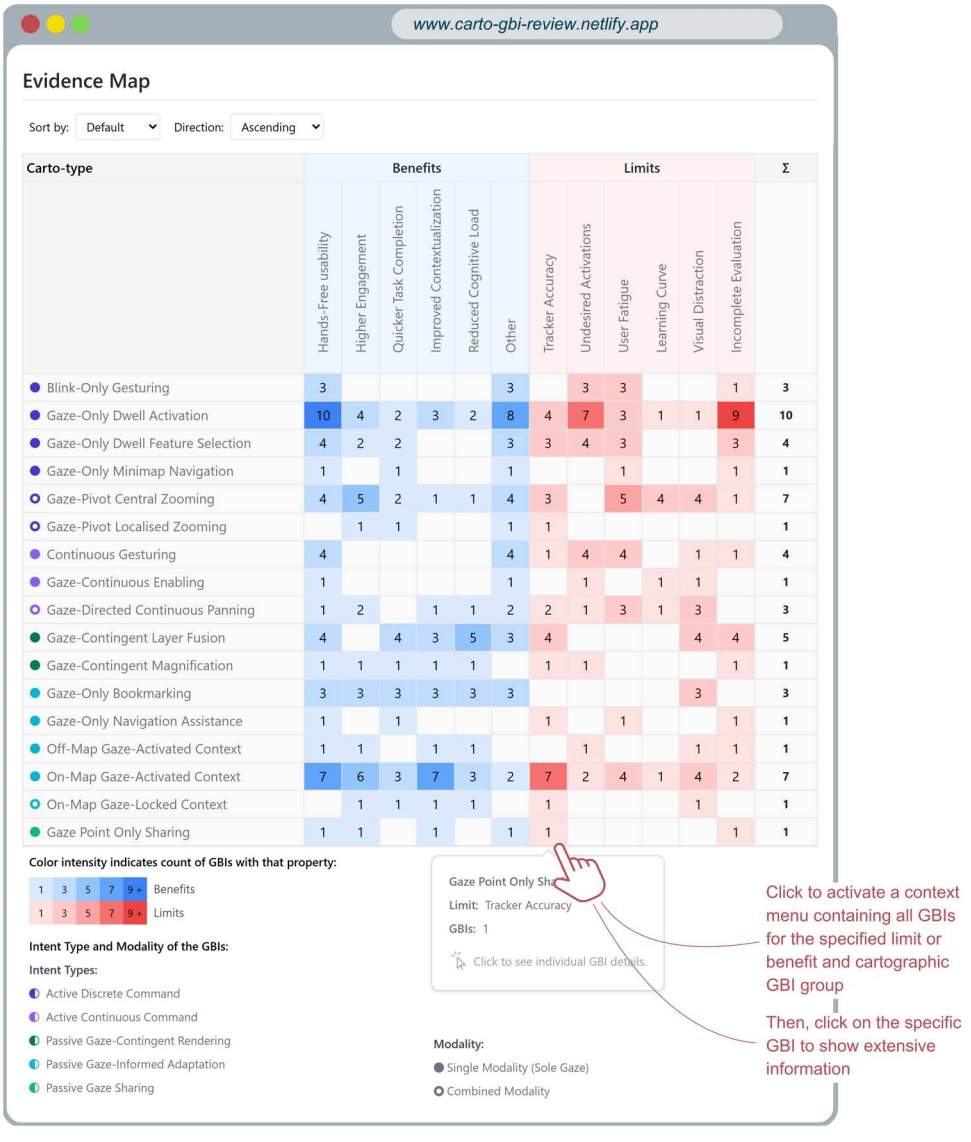

Figure 6. Interactive overview of recurrent benefits and limits of GBIs in geovisualisations.

adaptations where reading about a geographic location in a text automatically triggered the display of the corresponding location in an adjacent map. Active GBIs have also seen development, with the use of more complex mechanisms for controlling map interfaces.

Since 2020, advancements have primarily built upon established concepts, optimising the parameters for dwell-based map feature selection (Liao et al. 2022) or adapting them in new applications, such as on-map context adaptations through gaze-adaptive lenses for information-dense spaces (Goebel et al. 2020). Additionally, two articles examined active GBIs in XR environments, though nearly 90 percent of the review's GBIs were conducted on standard computer screens.

3.4.2. RQ2: which modalities and eye movement types do cartographic GBIs utilise?

Our review shows that most GBIs in cartography rely on the point-of-gaze, with over two-thirds using gaze as the sole modality. For active selections, the dwell time technique has been the most commonly used method from the start (largely because it is straightforward to implement), accompanying point-of-gaze to reduce the risk of unintended selections. Despite general GBI research exploring dynamic thresholds based on user intent or context (Isomoto, Yamanaka, and Shizuki 2022; Narkar et al. 2024), the reviewed articles predominantly relied on static thresholds, a long-established technique in the broader field.

In the 2010s, several studies combined gaze with non-gaze modalities to improve interaction precision. For instance, Stellmach and Dachselt (2012) combined gaze with mouse and touch input for zooming and panning, allowing the gaze to directly focus while manual inputs controlled action execution, and most utilised foot input (Klamka et al. 2015; Çöltekin et al. 2016). Only one passive GBI used a combined modality, where a mouse click locked gaze-adaptive lenses (Goebel et al. 2020).

A few passive GBIs calculated real-time fixations from point-of-gaze for enhanced functionality, such as in a gaze history application and adaptive legends, whereas Putra and Ogata (2022) departed from point-of-gaze entirely by employing gaze gestures (e.g. looking left, blinking) to emulate joystick movement over the map. Overall, gaze-only can maximise speed and convenience yet struggles with explicit confirmation steps, risking either unintended actions or user fatigue, while integrating gaze with secondary inputs (e.g. mouse or speech) offers more deliberate user control but may slow interaction and introduce a learning curve. As point-of-gaze remains the standard in cartographic GBIs, it remains an open question whether alternative eye movements could provide a more balanced trade-off between speed, certainty, and user control than single or combined modalities reliant on a point-of-gaze mechanism.

3.4.3. RQ3: what are the documented benefits of GBIs in cartographic interfaces?

GBIs offer significant benefits in cartographic interfaces by enabling hands-free operation, particularly for individuals with motor impairments and in situations where manual input is impractical. For example, Eaddy et al. (2004) demonstrated the use of gaze-controlled public kiosk maps, which allowed users to interact without physical touch – a feature that enhances accessibility and hygiene. Similarly, in virtual reality environments, gaze-based controls facilitate natural navigation through disaster scenes without handheld controllers (Zhang et al. 2022).

Moreover, participants consistently reported enhanced hedonic quality when using GBIs, indicating higher levels of enjoyment and engagement – even when GBIs are combined with hand input. This positive feedback has been documented not only through initial informal user reports, but increasingly through more standardised evaluations, such as the User Experience Questionnaire (UEQ) and NASA Task Load Index (NASA-TLX). For instance, showing gaze history led to lower physical and psychological demands and frustration, and better perceived effectiveness than the baseline map app (Göbel and Kiefer 2019). Gaze-adaptive legends scored even better with statistically significant improvements to standard legends (Göbel et al. 2018). However, these examples

were not compared to more advanced uses of traditional modalities, such as mouse position tracking, suggesting a gap in the comparison.

While many studies on active GBIs consider it beneficial when they are not significantly slower than traditional methods – making them a viable alternative for specific contexts – Zhang, Liao, and Meng (2024) have shown that these GBIs can be considerably faster in certain situations, such as map target selection after a search using the name of a place. In passive interactions, using gaze history – displaying previously viewed locations – leads to faster completion times in map search tasks (Giannopoulos, Kiefer, and Raubal 2013). Similarly, users completed counting tasks more quickly when identifying objects in aerial images with gaze-contingent rendering, which obscured peripheral details (Bektaş et al. 2019).

3.4.4. RQ4: what challenges are associated with implementing cartographic GBIs?

The problem of tracker inaccuracy is particularly critical in point-of-gaze GBIs, which most cartographic GBIs rely on. These limitations result in frustration, visual fatigue, and a diminished sense of control. To counter, many systems apply smoothing techniques, enlarge target areas, or add additional modalities. Furthermore, point-of-gaze GBIs necessitate calibration, which can further degrade the user experience, especially when tedious. The need for recalibrations – due to posture or environmental changes – only exacerbates this issue. While Pfeuffer, Zhang, and Gellersen (2015) offered a unique, seamlessly integrated calibration method where users tracked a moving object on a map (smooth-pursuit calibration), Göbel et al. (2018) used a chin-rest to prevent head movements. Developers can also reduce calibration drift by using head-mounted eye-trackers that stay fixed to the user's head. XR-integrated trackers go further by minimising external factors, yet only one reviewed study utilised this technology (Chalimas and Mania 2023). As eye-trackers become more common in consumer XR products, they also promise to address the frequently mentioned affordability barrier for sufficiently accurate eye-tracking, alongside increasingly precise webcam tracking (Saxena, Fink, and Lange 2024).

Another significant challenge is the 'Midas touch' problem – users reported frustration due to unintended activations in some active GBIs. Dwell times, the most commonly employed mitigation techniques, are effective to some extent, though they can introduce delays that lead to visual fatigue. The fatigue can be, however, mitigated with clear visual feedback. Combined modality approaches offered greater control but raised new complexities; for instance, coordinating gaze, hand, and foot inputs proved cognitively demanding (Çöltekin et al. 2016; Klamka et al. 2015). Moreover, non-point-of-gaze techniques – such as eye gestures intended to improve robustness under tracker inaccuracy – also triggered undesired actions, including involuntary blinks resulting in accidental map selections (Putra and Ogata 2022). Comparable issues arose in reviewed passive, gaze-informed adaptations, where misinterpreted gaze patterns occasionally led to inappropriate system responses.

Designing a GBI that preserves all aspects of user experience poses another challenge. Sudden gaze-triggered adaptations can feel abrupt, especially if they disrupt the natural gaze flow, causing cognitive overload or confusion. Adaptive map interfaces that present context near the user's gaze risk disrupting natural cognitive processes by introducing objects into the focal area of the working space. Active GBIs can present a non-trivial

learning curve when their complexity requires users to invest effort in mastering them (Putra and Ogata 2022). Furthermore, assessing GBI's impact on user experience is often less robust due to a lack of standardized evaluation measures and reliance on informal feedback. Similarly, some studies would benefit from stronger baselines, such as Goebel et al. (2020) comparing gaze-adaptive lenses with only a mouse-based counterpart, and Göbel et al. (2018) comparing gaze-adaptive legends only with static ones. Zhang et al.'s (2023) more comprehensive approach, comparing gaze-adaptive legends with static and mouse-based counterparts, provided a stronger assessment.

3.4.5. RQ5: where are the most significant research gaps in cartographic GBIs?

First, a common issue across the GBI field, including cartographic applications, is placing emphasis on technology rather than user experience (Mele and Federici 2012). Many reviewed studies relied on informal feedback or limited performance data, hindering comparisons and generalisations. Standardised questionnaires such as the NASA-TLX and UEQ with task completion times or similar for measuring such specific cartographic task performance as object searching, provide a more rigorous assessment. Moreover, comparing GBIs with such metrics to traditional modalities through proper baselines, would enhance interstudy comparisons (Zhang et al. 2023), though this practice was rare in the review.

Second, many challenges identified in cartographic GBIs mirror those successfully addressed from various angles in broader GBI research. Yet, they remain unexplored by cartographers. Advanced eye movement mechanisms, such as smooth pursuit and vergence, could be used in specific cartographic contexts for greater precision and reduced Midas touch problems with active GBIs (Esteves et al. 2015; Sidenmark et al. 2023). Tracking pupil dilation could bring real-time cognitive load estimation, which would improve passive GBIs and open new doors for them (Duchowski et al. 2018). Additional techniques, such as automatic continuous recalibration or integration of machine learning algorithms, could further improve the usability of gaze-enhanced interfaces (Isomoto, Yamanaka, and Shizuki 2022; Müller et al. 2019). A largely unexplored area is also the XR environment, for which GBIs are becoming a standard due to the success of consumer products with inbuilt eye-trackers.

Finally, the intent-response and modality divide of GBIs reveals several open directions, where creative integration of gaze-based input with new tasks and contexts could uncover further applications. *Combined modality* GBIs require further investigation. In active GBIs, combining gaze with ordinary computer peripherals could enhance interaction speed, while in XR environments, combinations with speech or head tilts could strengthen usability. The same applies to slightly underexplored passive GBIs, where additional modality could give users better control over the system and provide supplementary information about user activity.

4. Discussion

As Crampton (2002) emphasised, interactivity is central to geovisualisation, enabling dynamic engagement with spatial data. However, this review reveals that cartographic GBIs have lagged behind broader GBI advancements. While general GBI research has diversified into multimodal frameworks, adaptive intent recognition, and integration

with emerging technologies like XR, cartographic GBIs remain largely confined to desktop environments and rely on single-point-of-gaze mechanisms. While straightforward to implement, these methods illustrate a missed opportunity: Cartographers have yet to explore the full range of GBI design patterns from adjacent domains, many of which address the challenges identified here. Based on our findings, we propose five main future directions (FDs) below to diversify cartographic GBIs, improve usability, and align with standards such as ISO 9241-210.

4.1. Future directions

4.1.1. FD1: transforming active GBIs

Rather than relying solely on static dwell-time thresholds for gaze-based commands, we encourage exploring their use only when design constraints are well managed (e.g. avoiding overlap of actionable elements, minimising unintended selections with a balanced threshold, and reducing user fatigue with visual feedback). Additionally, these mechanisms should respect natural visual flow, as placing controls like pan buttons at screen edges may disrupt exploration. More adaptive approaches – such as dynamically adjusting thresholds based on gaze behaviour or inferring targets through machine learning – offer greater flexibility (Isomoto, Yamanaka, and Shizuki 2022; Müller et al. 2019). Alternative eye movements, such as smooth pursuits – although not explored in the reviewed studies – show promise as moving objects can be selected by correlating eye movement with the object's path with high precision, even without prior point-of-gaze calibration (Esteves et al. 2015). Such mechanisms could be particularly effective in geovisualisations with moving elements, such as transit or simulation environments. Another promising example could be adapting the Dasher interface (Ward, Blackwell, and MacKay 2000) for cartography, enabling continuous, gaze-driven pan and zoom of geovisualisation. Vergence could be explored as a switcher between pan, zoom, and free-viewing, maintaining gaze-only operation for users with limited motor access.

4.1.2. FD2: expanding the scope of passive GBIs

Despite early examples like gaze-contingent rendering (Nikolov et al. 2002), passive GBIs remain significantly underrepresented in cartography. Notably, the emergence of gaze history visualisations demonstrated clear benefits, such as aiding spatial orientation tasks by displaying previously viewed locations (Giannopoulos, Kiefer, and Raubal 2012; Göbel and Kiefer 2019) or adapting legend context based on previously viewed features (Göbel et al. 2018). The adaptive approaches could be extended by integrating real-time cognitive load metrics from different eye-movement metrics, such as pupil dilation or fixation dispersion (Duchowski et al. 2018), to enhance contextual relevance, reducing abrupt or intrusive system adaptations. Real-time cognitive load metrics could also serve in geographic education, tailoring the geovisualisation complexity to the user's needs. Additionally, extending passive GBIs to work with temporal components of the data could enhance multitemporal geospatial analysis. Gaze-contingent rendering, for instance, might highlight changes in raster data by suppressing unchanged regions in peripheral vision and emphasising altered areas in distinct colours. This approach lets users focus on present data while still being alerted to evolving patterns through peripheral cues.

4.1.3. FD3: combining modalities for the general population

Gaze-only systems – especially for command execution – remain vulnerable to undesired activations or user fatigue. While most reviewed cartographic GBIs utilised gaze alone, multimodal approaches – integrating gaze with secondary modalities like speech, touch, or head gestures – have demonstrated enhanced precision, robustness, and user control in general GBI research (Hou et al. 2023). The same pattern was observed in active cartographic GBIs. However, cartographers should consider not only the modality types but also their timing and synchronisation to avoid overloading the user and ensure fluid, natural interactions. Modalities should play complementary roles – e.g. gaze for rapid navigation combined with mouse control, a pattern that proved effective in gaze-pivot zooming in geovisualisation (Stellmach and Dachselt 2012). In general XR applications, simple combinations such as gaze pointing with head nod for confirmation have shown promising results (Hou et al. 2023). We also suggest that passive GBIs could benefit from multimodal integration – e.g. by modelling user behaviour over time through gaze patterns, click frequency, and interface actions – to enable more adaptive system responses.

4.1.4. FD4: considering environments with advantages for GBI

While desktop-based systems with remote eye-trackers remain useful for controlled research, they typically require expensive, high-precision equipment and calibration, limiting real-world usability. We suggest greater attention to contexts where gaze offers functional advantages or is natively available. For instance, XR headsets increasingly incorporate head-mounted eye-trackers that are stable relative to the head (Wang, Shi, and Liu 2023), reducing calibration drift and supporting robust gaze interaction without additional peripherals. Simple dwell-time mechanisms become more viable in this context, and gaze can be used to support navigation, object selection, or viewport control. In augmented reality, for example, field surveyors might trigger contextual overlays – such as property boundaries – via gaze, streamlining on-site tasks. Wearable eye-tracking glasses enable mobile, collaborative use cases. Inspired by broader GBI research, gaze sharing using torchlight-like beams in physical space (Akkil et al. 2016) could be adapted to participatory urban planning to enhance spatial communication between stakeholders. Likewise, in contexts requiring hygienic, hands-free interaction, gaze has been used in public displays (Vidal, Bulling, and Gellersen 2013), supporting the case for gaze-enabled public geovisual interfaces. Next, smooth pursuit control techniques explored in smartwatch interfaces (Esteves et al. 2015) may inspire novel GBIs for compact geovisual displays. Finally, emerging webcam-based solutions (Saxena, Fink, and Lange 2024) suggest that consumer-grade laptops and tablets may support GBIs without dedicated hardware – enabling lightweight, if less precise, gaze-enhanced geovisualisations on everyday devices.

4.1.5. FD5: adopting better evaluation frameworks

Moreover, the reviewed studies would benefit from more thorough evaluations, as only about one-fourth employed standardised user experience measures, and over half did not record any objective performance metric (e.g. task completion time). To enable meaningful interstudy comparisons and inform design choices, future studies should adopt robust evaluation methodologies, such as the NASA-TLX, UEQ, and speed and accuracy measures, as demonstrated by Zhang et al. (2023). Moreover, evaluations should go beyond

comparisons with static baselines and include advanced traditional modalities (e.g. mouse-based interfaces), especially when assessing new GBIs in applied settings. We also encourage collaboration between cartographers and GBI specialists to align interaction design with domain-specific usability demands while leveraging advanced technical capabilities.

4.2. Limitations of the review

First, reliance on a single researcher for article selection is the main limitation of the review, introducing potential selection bias. Although dual screening is recommended, single-researcher selection is not uncommon in focused scoping reviews when bolstered by mitigation strategies – in our case, a review protocol, iterative search refinement, AI-assisted tools for verification, the snowballing technique, and comprehensive supplementary materials for cross-checking the reporting.

Second, the review relied on informal feedback from original studies rather than standardised evaluation metrics, as nearly 50% of reviewed studies lack the latter. The ability to draw general conclusions about the effectiveness of GBIs across cartographic tasks is, therefore, limited. However, since this is a scoping review, its primary aim is to map the existing research rather than provide conclusive evidence.

Finally, while the number of included studies (n = 26) may appear limited, it aligns with the aims of scoping reviews in specialised domains such as cartographic GBIs and reflects the field's underdeveloped state. However, as the field consolidates and grows, a static overview risks becoming outdated. Hence, we present the results of individual sources of evidence and their categorisation via an interactive web-based viewer, which we plan to update for at least the next three years. The platform's open-source code is available in a public repository and can be adapted to other research areas, including promising studies on location-based services (LBS) that integrate geoinformation and GBIs, which we excluded from this review due to the absence of visual cartographic interfaces.

5. Conclusions

In conclusion, this scoping review offers the first in-depth examination of GBIs within cartographic interfaces, providing a foundational view of their implementation. Since their first use in 2002, cartographic GBIs have evolved significantly. Now, two-thirds of reviewed GBIs are active, allowing users to issue commands to cartographic interfaces and make map target selections through intentional eye movements. The remaining third ensures the adaptation of interfaces based on gaze patterns to optimise map detail in foveated rendering, and they adapt it to inferred user needs, or render gaze patterns to promote collaboration.

While most use a simple point-of-gaze, often with a dwell time threshold, as an underlying mechanism, some use different eye movements or combine gaze with additional modalities, such as computer mouse or feet. This modality can control, for example, zoom level, while gaze behaves as an anchor towards which the zoom occurs. Despite challenges such as insufficient accuracy and disruptions to natural gaze flow, many benefits were reported, including hands-free navigation and improved hedonic and pragmatic quality. However, the inconsistent reporting across studies highlights the need for enhanced evaluation standards in future research – ideally combining user experience measures (e.g. NASA-TLX, UEQ) with objective metrics and baseline comparisons with traditional modalities.

Expanding task variety, integrating multimodal interactions, and utilising usability solutions from broader GBI research – especially as consumer-grade XR devices with built-in eye tracking enable effective multimodal GBIs in other domains – offer a promising outlook for flexible cartographic interfaces. Geospatial systems could provide new ways to navigate and interact with complex datasets using a gaze modality, enhancing decision-making in fields such as urban planning and disaster response, user experience of digital maps, and geographic education efficiency.

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Data availability statement

All data, including the screening table, the review protocol, and the viewer source code, are deposited in the open repository at https://osf.io/ctgn6/.

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