Int. J. Human–Computer Studies 207 (2026) 103682

Contents lists available at ScienceDirect

International Journal of Human - Computer Studies

journal homepage: www.elsevier.com/locate/ijhcs

LLM-powered assistant with electrotactile feedback to assist blind and low vision people with maps and routes preview

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A R T I C L E   I N F O

Keywords:
Blind and low vision people
Electrotactile assistive tool
Maps and routes preview

A B S T R A C T

Previewing routes to unfamiliar destinations is a crucial task for many blind and low vision (BLV) individuals to ensure safety and confidence before their journey. While prior work has primarily supported navigation during travel, less research has focused on how best to assist BLV people in previewing routes on a map. We designed a novel electrotactile system around the fingertip and the Trip Preview Assistant (TPA) to convey map elements, route conditions, and trajectories. TPA harnesses large language models (LLMs) to dynamically control and personalize electrotactile feedback, enhancing the interpretability of complex spatial map data for BLV users. In a user study with twelve BLV participants, our system demonstrated improvements in efficiency and user experience for previewing maps and routes. This work contributes to advancing the accessibility of visual map information for BLV users when previewing trips.

1. Introduction

Trip preview refers to a process where travelers review the key aspects of an upcoming trip to understand what to expect during the trip. It is an important step in trip preparation because it ensures smooth, safe, and efficient travel. This process typically involves familiarizing oneself with key **map elements** such as destinations, landmarks' locations and details, and **travel route conditions**, including trajectory, weather, and traffic information (Borges Lopes et al., 2020; Golledge and Gärling, 2004). Conventional trip preview tools, like Google Maps and Trip Advisor, primarily convey travel information through visual and audio channels. However, blind and low-vision (BLV) users find it challenging to use these tools effectively due to the tools' reliance on visual information (Dove et al., 2022). The reliance on vision is a substantial issue for a large portion of the global population, as the World Health Organization estimates that approximately 2.2 billion people worldwide are affected by blindness or low vision (World Health Organization et al., 2024). For instance, BLV people may be less likely to visit an unfamiliar mall or attend an interview at an unfamiliar location, which restricts their life and work quality (Nagassa et al., 2023; Kulyukin et al., 2008). Thus, there is a pressing need for assistive tools specifically designed to enhance the trip preview process for BLV people.

Various haptic assistive tools have been developed to address the challenges faced by BLV users, including refreshable braille displays, tactile maps with 3D icons, and electrotactile devices, which help users build a map overview (Maćkowski et al., 2023; El Lahib et al., 2018; Reinders et al., 2025; Herman et al., 2025; Nagassa et al., 2023; Holloway et al., 2019; Hofmann et al., 2022; Lin et al., 2022; Dalgın et al., 2022; Jiang et al., 2024). Electrotactile interfaces create tactile sensations on the skin through localized electric currents (Kaczmarek et al., 1991). Unlike other haptic devices, electrotactile interfaces offer more flexibility by enabling users to switch maps rapidly and receive real-time traffic and weather information, empowering better destination and route decisions. Previous work has also highlighted the effectiveness of electrotactile feedback in supporting BLV users' understanding of visual information, such as charts when paired with audio feedback (Lin et al., 2022; Jiang et al., 2024). Maps share similarities with charts: both consist of basic shapes and following routes on a map is akin to tracing lines in a line chart. Drawing from these parallels, we sought to enhance the complexity of visual information conveyed through electrotactile feedback. Although electrotactile feedback is beneficial for conveying visual information, prior research has highlighted several challenges, including reduced perception over time and variations in sensitivity caused by factors such as skin-electrode

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https://doi.org/10.1016/j.ijhcs.2025.103682
Received 19 February 2025; Received in revised form 1 September 2025; Accepted 6 November 2025
Available online 8 November 2025

contact impedance (Lin et al., 2022; Withana et al., 2018). Traditional calibration methods and the use of conductive gels are time-consuming and may hinder user independence. BLV users currently have to ask sighted operators to calibrate the voltage or current for each electrode to ensure that the electrotactile feedback intensity is consistent (Lin et al., 2022; Jiang et al., 2024). This is crucial to avoid situations where the intensity might be too strong or too weak, which could lead to discomfort or reduced effectiveness of the feedback. These inefficiencies call for a more efficient approach to personalize electrotactile feedback based on individual sensitivities (Lin et al., 2022).

One approach to achieving personalization is through large language models (LLMs), which have been used to enhance accessibility for BLV people in various contexts, including understanding graphical information (Zhao et al., 2024; Hwang et al., 2024), navigation (Hwang et al., 2024; Wang et al., 2024), and education (Memarian and Doleck, 2023) LLMs have also been applied to trip planning and previews for sighted users, demonstrating their strengths in recognizing map elements (Zhang et al., 2024; Xie and Schwertfeger, 2024; Balsebre et al., 2024; Deguchi et al., 2024), understanding context (Wong et al., 2023; Li, 2023), responding to subtle nuances in spoken travel requests (Wong et al., 2023; Volchek and Ivanov, 2024; Hao et al., 2024), and providing personalized location recommendations and travel plans (Wong et al., 2023; Li, 2023; Volchek and Ivanov, 2024; Hao et al., 2024). Given the success of LLMs in assisting sighted users with trip previews, and the gap in such applications for BLV people, we leveraged LLMs to support BLV users in trip planning and previews. Moreover, researchers have highlighted the ability of LLMs to understand fuzzy requirements that stem from users' varying articulations of needs and nuanced preferences (Kasneci et al., 2023; Naveed et al., 2024), as well as their diverse capabilities for managing complex interaction scenarios (Thirunavukarasu et al., 2023). LLMs have also shown promise in generating personalized haptic feedback (Mishra, 2024), with findings suggesting that joystick vibration settings, adjusted by LLMs, enhanced gaming immersion (Mishra, 2024). Inspired by these studies, we used LLMs to personalize electrotactile feedback for BLV users, enabling our system to interpret various commands and adapt to individual needs, with the aim of enhancing convenience and efficiency.

To assist BLV individuals in trip preview, we developed a system combining an LLM-powered Trip Preview Assistant (TPA) and a finger-worn electrotactile device. The TPA has two main functionalities: (1) a voice interface to facilitate interaction with BLV users during trip previews, and (2) a control agent that enables the personalization of electrotactile feedback. The electrotactile device provides electrotactile feedback around the participants' fingertips with twelve electrodes. By integrating both the electrotactile system and the TPA, we designed two modes – map understanding, and route planning and exploration – which include 12 functions to support BLV users in previewing their trips. Through this system, we aimed to address the following research question (RQ):

How can an electrotactile system controlled by an LLM-powered TPA assist BLV people in trip previews?

We conducted a technical evaluation and a three-part user study with twelve BLV participants to answer this RQ. In the technical evaluation, we confirmed that LLMs personalized electrotactile feedback. In part 1 (perception of map elements and route conditions), we found that participants used the association memory method to efficiently recognize and memorize the electrotactile patterns. The participants achieved high accuracy in recognizing map elements (98.3%, SD = 3.0%) and route conditions (100%). In part 2 (map preview), we found that our system assisted participants in understanding the landmarks, spaces, and routes on the map since they achieved an average accuracy of 95% for all map preview tasks. We also discovered that BLV participants efficiently personalized the electrotactile feedback to enhance their map understanding by asking the TPA to adjust the intensity and provision. However, we identified a critical issue: the TPA occasionally produced hallucinations by providing non-existent information, which was difficult for participants to identify and validate. In part 3 (route preview), we found that electrotactile feedback integrated with the TPA assisted participants in creating and following a desired route. They achieved a low root mean squared (RMS) distance deviation (0.17 cm, SD = 0.08 cm) when following the electrotactile guidance, indicating that participants precisely followed the intended trajectory. In summary, our user study showed that the electrotactile patterns and TPA efficiently assisted BLV participants in trip previews.

Our contributions include:

1. We designed a novel electrotactile system around the fingertip for BLV people to perceive map elements (e.g., buildings/rooms, greenspaces) and route conditions (E.g., traffic and weather) before a trip;
2. We designed an LLM-powered Trip Preview Assistant (TPA) that personalizes electrotactile feedback intensity and activates the corresponding electrotactile patterns for BLV people when they preview a trip on a map;
3. We conducted a user study to understand how the LLM-powered TPA controlled the novel electrotactile patterns to assist BLV people in map and route preview.

2. Related work

2.1. Electrotactile assistive tools for BLV people's trip preview

Trip preview is the initial step during trip preparation, where users familiarize themselves with map elements and route conditions, such as destinations, landmarks, weather, and traffic (Borges Lopes et al., 2020; Golledge and Gärling, 2004). This process typically relies on commercial applications like Google Maps, Apple Maps, and Trip Advisor, which provide travel information through visual and audio channels (Dove et al., 2022; Borges Lopes et al., 2020). However, BLV users face challenges using these apps, such as difficulties in locating POIs on maps, understanding their relative positions, and memorizing routes without a comprehensive map overview (Dove et al., 2022; Stephens et al., 2020; Nagassa et al., 2023). This lack of overview reduces confidence and increases reliance on real-time voice guidance, which may distract them from environmental awareness and raise collision risks (Stephens et al., 2020; Nagassa et al., 2023).

To address these challenges, researchers have developed haptic assistive tools like refreshable braille displays, tactile maps with 3D icons and electrotactile devices, which help BLV users build a map overview (Maćkowski et al., 2023; El Lahib et al., 2018; Tekli et al., 2018; Darin et al., 2022; Fink et al., 2023; Reinders et al., 2025; Herman et al., 2025; Nagassa et al., 2023; Holloway et al., 2019, 2018; Albouys-Perrois et al., 2018; Hofmann et al., 2022; Lin et al., 2022; Dalgın et al., 2022; Jiang et al., 2024). Electrotactile interfaces use localized electric currents to create tactile sensations on the skin Kaczmarek et al. (1991), offering more flexibility than other haptic devices by allowing users to switch maps rapidly and receive real-time traffic and weather information, helping users make better destination and route decisions. Moreover, prior work showed that electrotactile feedback supports BLV users in building an intuitive understanding of visualizations, such as charts, by rendering chart elements in addition to audio feedback (Lin et al., 2022; Jiang et al., 2024). Comprehending maps is akin to understanding charts: maps are made up of basic shapes, and following routes is similar to tracing the trajectory of a line in a line chart. Therefore, we were inspired by this work and aimed to enhance the complexity of visual information conveyed through electrotactile feedback.

Despite these potential capabilities, BLV users face challenges with electrotactile feedback, including reduced perception over time and varying sensitivity due to factors like skin-electrode contact impedance (Lin et al., 2022; Withana et al., 2018; Jiang et al., 2024). These issues have been addressed through calibration methods and conductive

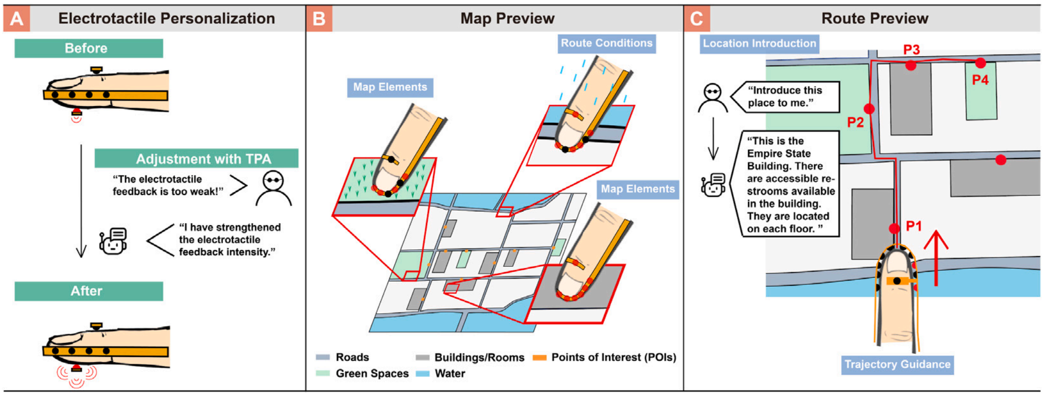

Fig. 1. Overview of the Trip Preview System: (A) Electrotactile personalization: The red cylindric dot represents an electrode that applies electrotactile feedback on the fingertip. In this scenario, the BLV user complains about the weakness of electrotactile feedback to the Trip Preview Assistant (TPA). Then, the TPA responds by increasing the electrotactile feedback's intensity. (B) Map preview: The user perceives the map elements (green spaces and buildings/rooms) and route conditions (rainy weather) with various electrotactile patterns. (C) Route preview: The user follows the electrotactile guidance after asking the TPA to plan a route trajectory through various points of interest (P1, P2, P3, and P4). During the guidance, the user asks for information about P1. The legends of various map elements are shown at the bottom.

gels (Jiang et al., 2024; Lin et al., 2022), but these solutions can be time-consuming and may hinder user independence. Therefore, a more efficient and accessible approach is needed for BLV users to personalize electrotactile feedback based on individual conditions such as their different sensitivities to electrotactile feedback.

2.2. LLMs for BLV people's trip preview

Recent advances in LLMs, such as ChatGPT, have demonstrated potential to assist BLV users across various domains, including understanding graphical information (Zhao et al., 2024; Hwang et al., 2024; Yang et al., 2024), navigation (Hwang et al., 2024; Wang et al., 2024), and education (Memarian and Doleck, 2023). Many prior works using LLMs for navigation have focused on providing real-time assistance, such as detecting incoming pedestrians and obstacles (Hwang et al., 2024; Wang et al., 2024). However, the potential for LLMs to assist BLV individuals in planning and previewing trips has been relatively underexplored.

Given that trip preparation is crucial for their travel experience, the absence of such tools may reduce their trip efficiency, negatively impact their experience, and increase the risks associated with their trips. In contrast, LLMs have been widely applied to trip planning and previews for sighted users, where researchers have identified several benefits. These include their strong capability for recognizing map elements (Zhang et al., 2024; Xie and Schwertfeger, 2024; Balsebre et al., 2024; Deguchi et al., 2024), context understanding (Wong et al., 2023; Li, 2023), sensitivity to subtle nuances in spoken travel requests (Wong et al., 2023; Volchek and Ivanov, 2024; Hao et al., 2024), and the ability to provide personalized location recommendations and travel plans (Wong et al., 2023; Li, 2023; Volchek and Ivanov, 2024; Hao et al., 2024). For example, Wong et al. explored how LLMs can enhance the tourist experience across three travel stages: pre-trip, en-route, and post-trip. They found that LLMs offer highly cost-effective travel solutions through multi-round conversations, providing customized information tailored to users' nuanced needs and enabling tourists to travel with ease (Wong et al., 2023). Given the lack of exploration into how LLMs could assist BLV individuals with trip previews, and inspired by the success of LLMs in supporting sighted people's trip planning, we have leveraged LLMs to help BLV individuals in trip planning and previews.

Furthermore, previous studies have highlighted LLMs' ability to understand fuzzy requirements, which arise from users' varying abilities to articulate their needs and the nuanced differences in their preferences (Kasneci et al., 2023; Naveed et al., 2024), as well as their capacity to handle complex interaction scenarios (Thirunavukarasu et al., 2023). The potential for LLMs to create personalized haptic feedback has also been explored (Mishra, 2024), with findings indicating that joystick vibration settings, adjusted by LLMs, enhanced the immersion of playing video games (Mishra, 2024). Inspired by these capabilities, we applied LLMs to personalize electrotactile feedback for BLV individuals through understanding various commands and adapting to their needs, making the tool more convenient and efficient for BLV users.

3. Electrotactile patterns and trip preview assistant (TPA) design

3.1. Trip preview needs and design of electrotactile patterns

This section introduces the basic electrotactile patterns selected for our system, followed by additional patterns that were tailored to meet trip preview requirements.

3.1.1. Basic electrotactile pattern design for location and direction notifications

We employed two basic electrotactile patterns: **Location Notification** and **Direction Notification**, shown in Fig. 2. **Location Notification** used a single electrode to mark specific locations, while **Direction Notification** employed sequential two-point stimulation to convey directional cues, indicating movement from a starting point to an endpoint. Previous studies have shown that directional cues using this method have an accuracy deviation of less than 10 degrees, which is sufficient for applications like charts that require general directional guidance, a level of precision that is equally applicable to map-based notifications (Lin et al., 2022; Jiang et al., 2024). Given that rendering maps requires less precision than charts, these basic patterns were well-suited for conveying map information effectively.

3.1.2. Electrotactile pattern design for map elements and route conditions

The electrotactile patterns designed for map elements and route conditions involved combinations of location and direction notifications. Map elements, such as roads, buildings/rooms, points of interest (POIs), water, and greenspaces, were defined following established guidelines from previous research (Hofmann et al., 2022; Götzelmann, 2016; Nagassa et al., 2023; Palivcová et al., 2020). Route conditions included traffic and weather details like high or low traffic, and weather variations such as sunny, cloudy, or rainy/snowy conditions.

Map Elements Patterns. These patterns helped participants form a mental map overview by conveying the layout of different areas and

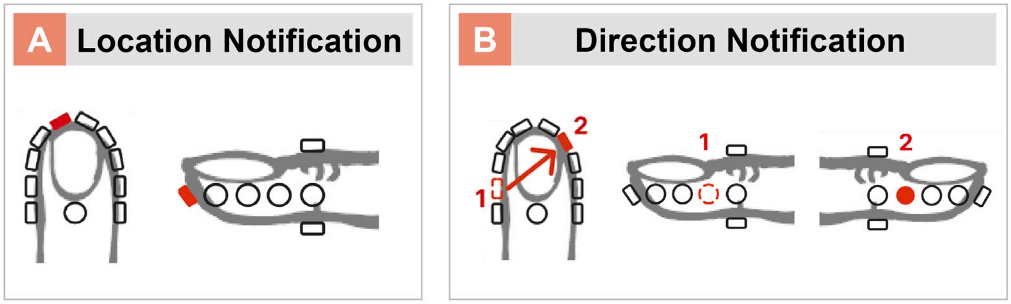

Fig. 2. Basic Electrotactile Patterns: (A) Location notification. The red squares represent the electrode that is applying electrotactile feedback. (B) Direction notification. The red square and circle drawn by the dashed line is the beginning electrode applying electrotactile feedback (marked by 1). The red square and circle drawn by the full line is the ending electrode applying electrotactile feedback (marked by 2). The sequential stimulations of electrodes 1 and 2 provide the direction notification to the users. The direction vector starts from electrode 1 and ends at electrode 2.

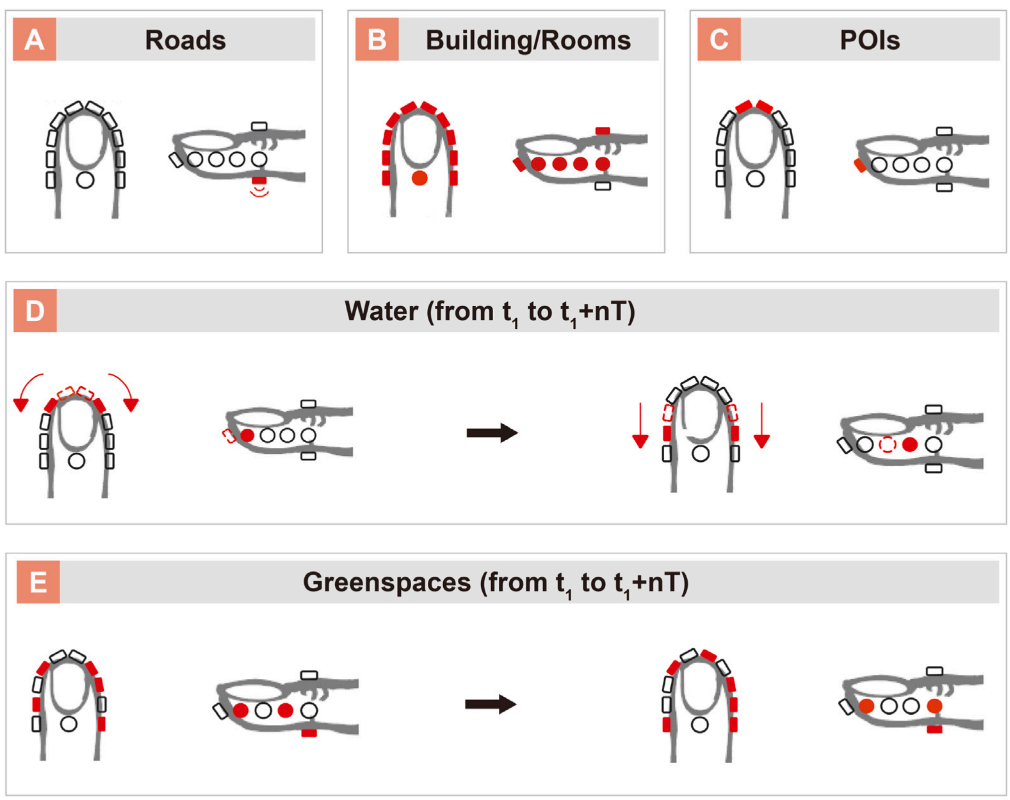

Fig. 3. Electrotactile Patterns for Map Elements: (A) Roads: continuous stimulation on the fingertip pad; (B) Buildings/rooms: continuous stimulation on the backside of the finger and fingertip edge; (C) POIs: continuous stimulation on the fingertip edge's two top points (points 5 and 6); (D) Water: periodic moving stimulation on the fingertip edge from top to bottom (points 5 to 1, and points 6 to 10); (E) Greenspaces: random stimulation on the fingertip pad and fingertip edge.

landmarks. Each element was represented through distinct electrotactile patterns based on the relative position of the user's finger to map features and their real-life haptic perceptions, as shown in Fig. 3.

Roads were represented by continuous fingertip pad stimulation, indicating the user was over a road (Fig. 3A).

Buildings/rooms were marked by continuous stimulation on the backside of the finger and fingertip edge, reflecting their typical height in relation to the user (Fig. 3B).

POIs were identified by continuous stimulation on the fingertip edge's top two electrodes (5 and 6), indicating proximity to a POI (Fig. 3C).

Water was represented by periodic, moving stimulation from the fingertip's top to bottom edge, mimicking the sensation of flowing water (Fig. 3D).

Greenspaces like grasslands or forests were represented by random stimulation across the fingertip, simulating uneven surfaces (Fig. 3E).

Route Conditions Patterns. Route conditions patterns allowed participants to interpret predicted traffic and weather conditions at specific locations. These included high and low traffic, and weather conditions like sunny, cloudy, and rainy/snowy. The patterns were designed to reflect users' haptic perceptions of these conditions, as depicted in Fig. 4.

Traffic was indicated by intermittent fingertip pad stimulation, with frequency correlating to traffic density: higher frequency for *high traffic* and lower frequency for *low traffic* (Figs. 4A and 4B).

Sunny weather was marked by continuous stimulation on the backside of the finger, simulating constant sunlight (Fig. 4C).

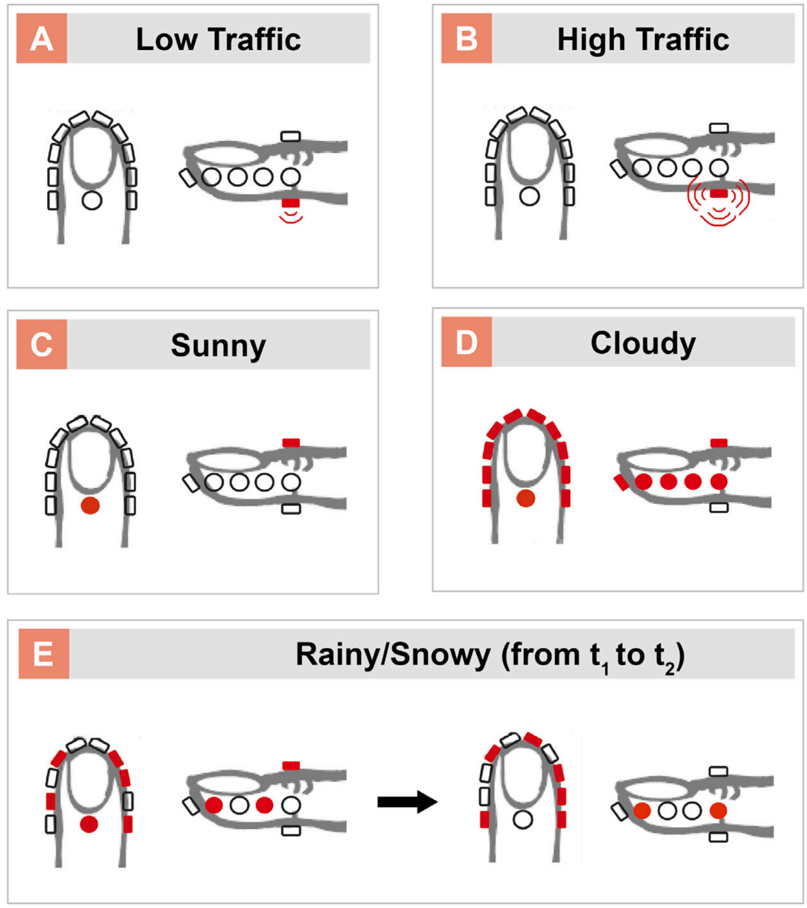

Fig. 4. Electrotactile Patterns for Route Conditions: (A) Low traffic: intermittent low-frequency stimulation on the fingertip pad; (B) High traffic: intermittent high-frequency stimulation on the fingertip pad; (C) Sunny: continuous stimulation on the backside of the finger; (D) Cloudy: continuous stimulation on the backside of the finger and fingertip edge; (E) Rainy/snowy: random stimulation on the backside of the finger and fingertip edge.

Cloudy weather was indicated by simultaneous stimulation on both the backside and fingertip edge, mimicking the presence of clouds (Fig. 4D).

Rainy/snowy weather was represented by random stimulation across the backside and fingertip edge, simulating raindrops or snowflakes (Fig. 4E).

3.2. Implementation of electrotactile patterns

To implement the electrotactile patterns for assisting BLV people's trip preview, we developed an electrotactile system that applied feedback around the fingertip using a two-channel modulated signal. As shown in Figs. 5 and 6(B), the system consists of three main components: signal generation, stimulation control, and electrotactile feedback application.

The **signal generation** component used a dual-channel signal generator to produce two modulated signals with opposite phases, enabling high-frequency vibration perception (Lin et al., 2022). The first signal was a 1 kHz positive square wave (1Vrms), amplitude-modulated by a 40 Hz sine wave. The second signal mirrored the first but was phase-shifted by 180 degrees. Both signals were amplified to ensure sufficient voltage for tactile perception.

Stimulation control was managed by twelve sets of relays connected to an Arduino Mega board. These relays controlled the distribution of the amplified signals (positive or negative) to the electrodes. When a positive signal was applied to an electrode, and adjacent electrodes were connected to a negative signal, electrotactile feedback would activate the skin under the positive electrode (Jiang et al., 2024; Lin et al., 2022; Kajimoto, 2011).

The **electrotactile feedback application** consisted of a customized Flexible Printed Circuit (FPC) worn on the fingertip. The FPC had ten electrodes along the fingertip's edge (labeled 1 to 10), with additional electrodes on the backside of the finger (12) and fingertip pad (11), as shown in Fig. 6(C). These electrodes enabled accurate electrotactile stimulation.

Precise **finger tracking** was essential for delivering accurate feedback. We used a camera placed above the participant's hand to track the fingertip's position in real time, utilizing a system of color-coded markers. Ten green markers were placed on the backside of each electrode, and a purple marker was placed on the backside of the finger, aligned with the fingertip pad (Fig. 6B). A custom algorithm detected and tracked these markers based on their color and contours.

For **safety assurance**, we implemented a strict safety protocol, following procedures from prior research (Jiang et al., 2024; Lin et al., 2022). The system included emergency cut-off buttons and an integrated control algorithm that automatically halted electrotactile feedback if the voltage exceeded safety limits (50 V) set by the International Electrotechnical Commission (IEC).

3.3. Using LLM-powered trip preview assistant to address electrotactile feedback challenges

We explored the challenges related to electrotactile feedback, as discussed in Section 2.1, and developed an LLM-powered TPA to enable

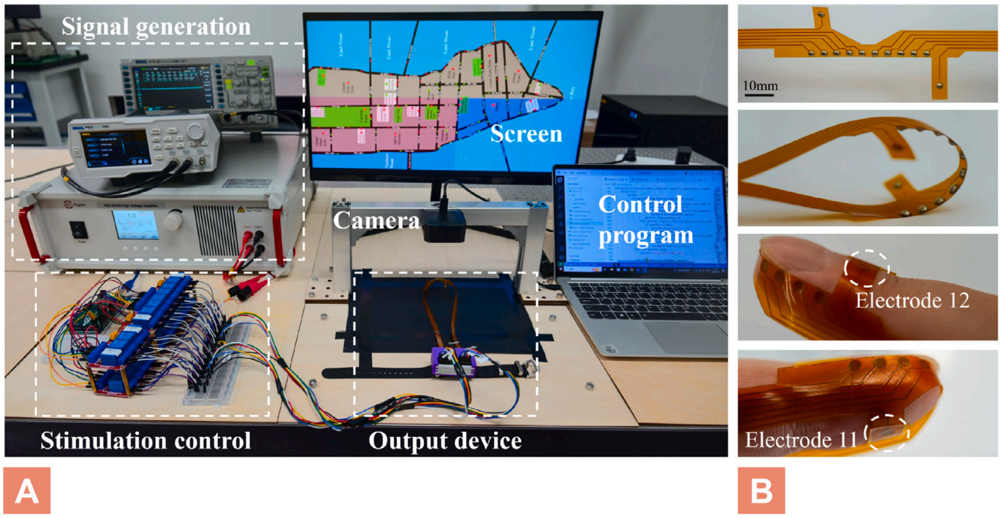

Fig. 5. Photograph of the Trip Preview System: (A) The overview of the system; (B) The close view of the customized FPC showing the arrangement of electrodes, the flexibility of the FPC, and the location of the electrodes after wearing FPC, especially the locations of electrode 11 and electrode 12.

personalized feedback. The TPA interacts with BLV users to assist with trip previews and customize electrotactile feedback. Various prompt engineering techniques (Wei et al., 2022; Ji et al., 2023) were employed to optimize the model's performance. The TPA consists of three agents: the **overarching control agent**, the **electrotactile personalization agent**, and the **trajectory planning agent**, as shown in Fig. 6(A). All agents leverage OpenAI's GPT-4o model for fast responses and multimodal input processing (OpenAI, 2023).

The **overarching control agent** manages the entire system, handling user interactions, activating the appropriate agent based on user requests, and enabling different functions. It accepts voice inputs from BLV users via OpenAI's Whisper (OpenAI, 2024b), converts them to text, processes the requests, and directs them to the relevant agent. The response is then converted into audio using Text-to-Speech (TTS) technology (OpenAI, 2024a).

The **electrotactile personalization agent** helps BLV users adjust the intensity, direction, and patterns of the electrotactile feedback. This agent receives inputs and adjusts the voltage and stimulation positions. In addition to manual adjustments by the moderators, participants could use voice commands to interact with the TPA, such as increasing or decreasing the voltage during calibration and throughout the experiment session (Fig. 1A). Their requests could be either precise or fuzzy. For example, precise prompts could include commands such as "increase by 3 V" or "turn left about 15°", whereas fuzzy prompts might be expressed as "decrease a little bit" or "turn right slightly". Fuzzy prompts were interpreted by the system using predefined tolerance ranges to ensure appropriate adjustments. In addition, though they could not personalize the encodings of map elements or route conditions, they could request the TPA to temporarily suspend feedback from one of them to focus on others.

Few-shot learning and Chain of Thought prompting techniques were used to enhance the agent's accuracy (Ji et al., 2023). A safety mechanism ensures that the voltage remains within safe limits.

The **trajectory planning agent** assists BLV users in planning their trip routes. It uses optical character recognition (OCR) to extract place names from maps (Rakpong Kit, 2022), integrating this data with real-world route and weather conditions to help users modify their trip trajectories. The agent can update destinations with precise prompts, such as "add Central Park" or "I want to visit the Chrysler Building". The process is shown in Fig. 1C. It can also handle fuzzy requests, like "avoid crowded or rainy areas" or "take me to the park you just mentioned".

To assess LLM effectiveness in personalization, we conducted a technical evaluation using both vague and precise prompts to adjust feedback parameters, as detailed in Table 4. Our findings confirmed that LLMs could efficiently personalize electrotactile feedback, allowing us to integrate them into our system.

3.4. Design of two modes for trip preview

Building upon prior research on presentation modes for charts (Abu Doush et al., 2010; Jiang et al., 2024), we developed two primary modes for our assistive tool: **Map Understanding** and **Route Planning and Exploration**, which are shown in Table 1. The column "**Control via TPA**" defines when participants were allowed to access specific functions. Specifically, **when touching element** indicates that participants could activate a function whenever they were touching a specific map element. Additionally, **anytime except guidance** indicates that the function could be used at any time except when the participant was engaged in the *trajectory guidance* process. These modes offer BLV users comprehensive trip preview assistance through twelve distinct functions, which are outlined below.

Map Understanding helps users gain an overview of the map. It includes five key functions:

1. *Title Reading*: Reads the map's title aloud.
2. *Map Briefing*: Provides a brief introduction to the map's points of interest (POIs) and areas.
3. *Location Report*: Reports the current street/corridor and POI names.
4. *Location Introduction*: Gives detailed information about the current POI.
5. *Map Elements Notification*: Uses electrotactile patterns to notify users about various map elements, as detailed in Section 3.1.2 and is shown in Fig. 1B.

Route Planning and Exploration assists users with planning, navigating, and managing their trip routes. It includes seven functions:

1. *Trajectory Planning*: Allows users to plan a trip trajectory automatically. They can add or delete destinations and replan the route at any time.
2. *Trajectory Guidance*: Guides the user's finger along the planned trajectory, providing audio updates on each destination.
3. *Location Guidance*: Directs the user's finger to a specified destination.
4. *Start Point Guidance* and *End Point Guidance*: Guides users to the start and end points of the current trajectory, reading out the names aloud.

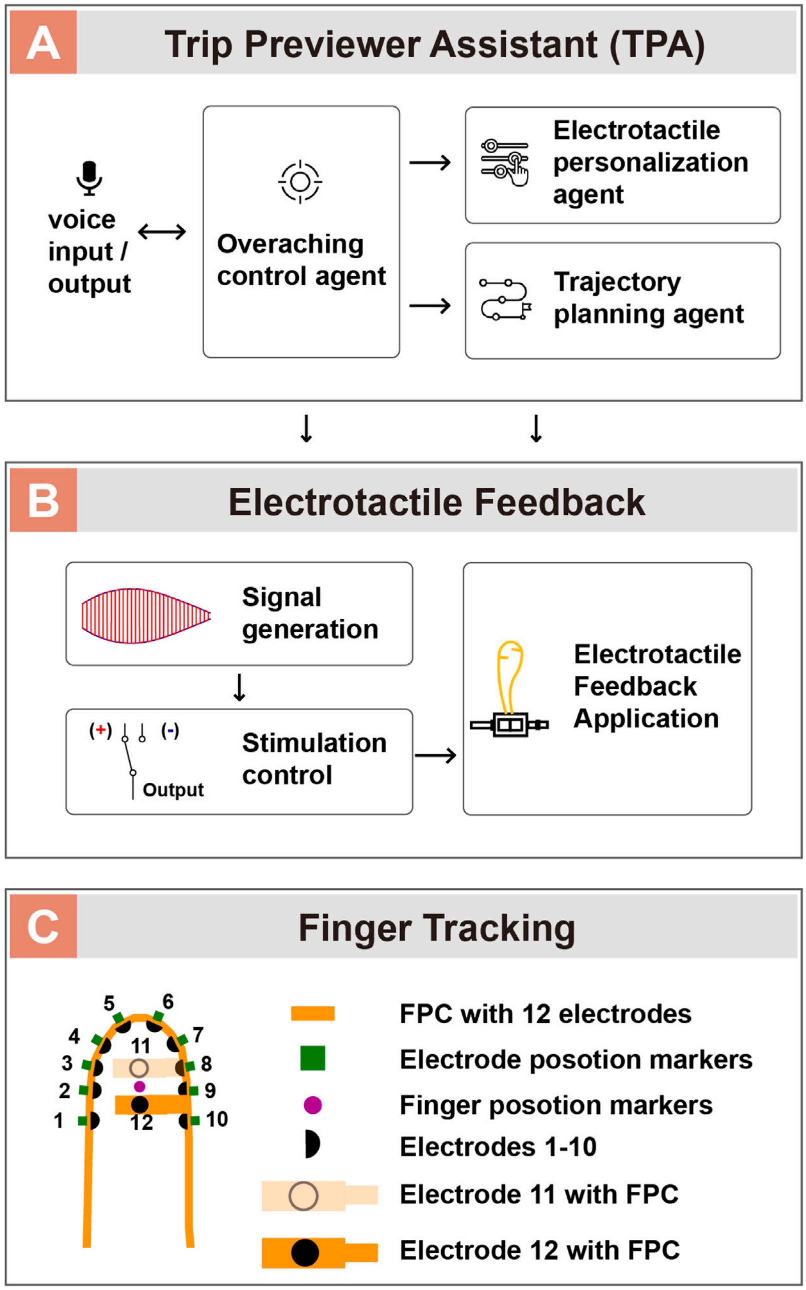

Fig. 6. The Trip Preview System Diagram: (A) The TPA component consists of three key agents: overarching control agent, electrotactile personalization agent, and trajectory planning agent; (B) The electrotactile feedback component includes three parts: signal generation, stimulation control, and electrotactile feedback application; (C) Finger tracking component: A camera mounted above the hand captures the positions of fingers and electrodes in real-time using a custom computer vision algorithm and colored markers.

5. *Route Conditions*: Provides information on predicted traffic and weather at specific times and locations, based on forecast data. The corresponding electrotactile patterns are outlined in Section 3.1.2 and are shown in Fig. 1B.
6. *Plan Saving/Loading*: Allows users to save the current trip trajectory or load a previously saved route.

The *Map Elements Notification* function is set as the default. Therefore, participants must explicitly request the TPA to switch to the *Route Conditions* function when needed. This ensures users can properly interpret the information provided by each function.

4. User study

We conducted a user study to evaluate how our system could assist BLV users with trip preview. The study consisted of three parts: In part 1, we evaluated how accurately participants could perceive map elements and route conditions. In part 2, we evaluated how the system could assist participants in map preview. In part 3, we evaluated how the system could assist participants in route preview.

4.1. Participants, apparatus, selection of maps and tasks

We recruited 12 participants (5 males, 7 females) from the local community with various visual conditions (low vision to fully blind)

Table 1
Eleven functions in two types of supports: (a) Map understanding; (b) Route planning and exploration.

Supports	Function	Description	Control via TPA
Map Understanding	Title Reading	Report the current map's title	Anytime
	Map Briefing	Give a brief introduction of the map	Anytime
	Location Report	Report the current location's name	when touching element
	Location Introduction	Introduce the current location	when touching element
	Map Elements Notification	Notify the current map element	when touching element
Route Planning and Exploration	Trajectory Planning	Plan a trip trajectory	anytime except guidance
	Trajectory Guidance	Guide the finger along the planned trip trajectory	anytime except guidance
	Location Guidance	Guide the finger to the required trip location	anytime except guidance
	Start/End Point Guidance	Guide the finger to the start/end point of the trip trajectory	anytime except guidance
	Route Conditions	Display traffic and weather	when touching element
	Plan Saving/Loading	Save or load the trip trajectory	anytime except guidance

Table 2
BLV participants' demographic information.

ID	Gender	Age	Vision level	Congenital?
1	M	33	Totally blind	No
2	F	24	Low vision	Yes
3	M	35	Totally blind	No
4	F	27	Totally blind	Yes
5	F	22	Totally blind	No
6	F	21	Totally blind	No
7	M	26	Low vision	Yes
8	M	42	Low vision	No
9	F	33	Totally blind	No
10	M	36	Totally blind	No
11	F	25	Totally blind	Yes
12	F	26	Totally blind	Yes

with an average age of 29.2 (SD = 6.5), as shown in Table 2. All participants had no implants or heart-related diseases. All participants reported having no prior experience with electrotactile assistive tools, though all had used tactile graphics during their middle school education. Most participants (10/12) regularly used map applications (e.g., Baidu Maps, Apple Maps) for daily navigation. Among the three low vision participants, two mentioned that they could only perceive vague visual information, such as large color blocks.

Participants sat comfortably with their right arm resting on a table, and their index finger equipped with the FPC. They could place their finger on the table or in the air, depending on their preference. The maps were rendered using Python's CV2 library, visible only to the operator, while participants were free to move their fingers on the table.

4.2. Selection of maps

Two maps were used in the study: an outdoor map (MO) and an indoor map (MI), which are shown in Fig. 7. MO was used in all three parts, while MI was used in Parts 2 and 3. These maps, designed based on Google Maps, featured common map elements like roads, buildings/rooms, POIs, water, and greenspaces, customized for the study (Hofmann et al., 2022; Götzelmann, 2016; Nagassa et al., 2023; Palivcová et al., 2020). Our design aimed to represent real-world environments through these elements, helping participants understand map layout and route conditions.

4.3. Selection of tasks

In **Part 1**, we selected two tasks to evaluate participants' perception of map elements and route conditions. In the first task, participants were asked to report their perceived map elements in random order. In the second task, they were asked to identify randomized route conditions, including weather and traffic conditions. Each map element or route condition was tested three times, and participants' responses were collected for every trial.

In **Part 2**, we evaluated the effectiveness of our system in map preview with eight tasks, based on Griffin et al.'s 2020 designs. Before starting the tasks, participants were given 5 to 10 min to freely explore the map and build a mental overview. These tasks were divided into three task groups: **Landmarks**, **Spaces**, and **Routes**, shown in Table 3. **Landmarks** includes streets/corridors listing (T1) and points of interest listing (T2). For T1, participants were asked to freely explore the map and list four street names (MO) or corridor names (MI). For T2, participants should list four POIs after their exploration process.

Spaces includes location estimation (T3), direction estimation (T4), and direct distance estimation (T5). For T3, we divided the map into four quadrants. Participants were given a POI and asked to identify in which quadrant it was located. For T4, participants were given two POIs and asked to report the direction of the line connecting them. For T5, participants were given two groups of POIs, each containing two POIs, and were asked to identify which group had the longer connecting line.

Routes includes route distance estimation (T6), route recognition (T7), and wayfinding (T8). For T6, participants were given two groups of POIs, each containing two POIs, and were asked to explore the map along streets/corridors to compare the routes connecting each group and identify the longer route. For T7, participants were presented with a route connecting two POIs along streets/corridors and asked to determine whether it was the shortest route, providing reasons for their judgment. For T8, participants were given two POIs and asked to describe the route from the start point to the end point, mentioning any POIs passed along the way.

In **Part 3**, participants completed a single task to evaluate route preview with our system. They were asked to plan routes under two conditions on both MO and MI: with and without route conditions (such as traffic and weather). Each participant completed a total of four trials (2 maps $\times$ 2 conditions). The sequence of maps was randomized. For each map, participants first completed the trial without route conditions, followed by the trial with route conditions.

In the **without-route trial**, participants explored the map and asked the TPA to suggest POIs according to their preferences. They then selected four POIs and asked the TPA to generate a route plan. The number of POIs was fixed at four, as participants reported that this matched their average daily visit count and allowed for manageable

Fig. 7. Maps Used in User Study: (a) Outdoor map: Revised New York City Map; (b) Indoor map: Revised Horizon Building Map. The red dots were the entrance to each landmark.

Table 3
Preliminary strategies and challenges for maps preview tasks.

Task groups	Tasks	Preliminary strategies	Challenges
Landmarks	(T1) Streets/Corridors listing	rapid exploration	N/A
	(T2) Points of interest listing	rapid exploration	N/A
Spaces	(T3) Location estimation	POI location comprehension, map edge comprehension	N/A
	(T4) Direction estimation	POI location comprehension	N/A
	(T5) Direct distance estimation	POI location comprehension	N/A
Routes	(T6) Route distance estimation	POI location comprehension, route exploration	Difficulty with following the roads and memorizing routes
	(T7) Route recognition	POI location comprehension, route exploration, route comparison	Difficulty with following the roads and memorizing routes
	(T8) Wayfinding	POI location comprehension, route exploration	Difficulty with following the roads and memorizing routes

adjustments (e.g., adding or removing one POI). After the route was determined, participants were guided by the TPA through electrotactile feedback. They were first guided to the start point, then along the streets/corridors connecting each POI in sequence, and finally to the end point.

In the **with-route trial**, participants repeated the same process (map exploration, POI selection, and guided navigation), but with additional route conditions (e.g., weather or traffic). The same sequence (from the without-route trial to the with-route trial) was then repeated for the second map. After each trial, participants rated their confidence in the planned route. These ratings, along with qualitative feedback on their ratings, were audiorecorded. In addition, participants' movement trajectories during each trial were captured using computer vision (CV) tracking of position markers on the FPC.

4.4. Study procedure

We first introduced the experimental setup to the participants, with particular emphasis on the wearable device. To ensure optimal conductivity, participants were asked to clean and dry their right index

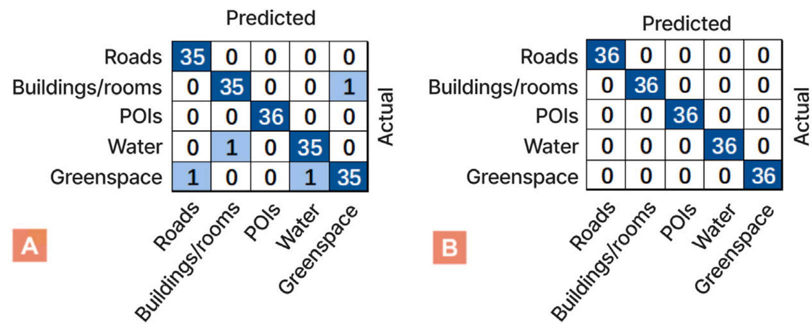

Fig. 8. The confusion matrix of part 1 results. (a) the results of map elements recognition; (b) the results of route conditions recognition.

finger. The device was then attached to their fingers, ensuring that the FPC was centered and positioned symmetrically. Participants were guided to touch the FPC and markers with their other hand to become familiar with the location of each electrode.

Next, we conducted a calibration process to ensure consistent and perceivable electrotactile stimulation across the twelve electrode positions. Calibration was critical because skin-electrode contact impedance can vary due to factors such as skin humidity, temperature, and thickness, potentially leading to unequal sensations (Fortune et al., 2021; Murphy et al., 2021). We followed protocols established by Lin et al. and Jiang et al. with minor revisions to accommodate our new functionalities (Lin et al., 2022; Jiang et al., 2024).

Calibration began at 5 V for each electrode, starting from position 1, and the voltage was gradually increased until the participant reported a sensation level of 3 on a 5-point Likert scale (1: no perception, 5: very strong perception). Customized voltages were then set for each electrode and adjusted until sensations were consistent across positions. These final voltage settings were used in all subsequent experiments. Initially, the voltage adjustments were made by the testers. The participants could also request the TPA to adjust the voltage if any electrode was not clearly perceivable or if sensations were uneven across positions.

After calibration, participants completed a training session to familiarize themselves with each function. The training was conducted on a simplified MO to provide a consistent experience without allowing participants to build a full mental overview that might influence the subsequent user study. A moderator first introduced each function, and participants were encouraged to explore them either freely (e.g., map element notifications, location reporting) or by interacting with the TPA (e.g., title reading, map briefing). During the session, participants could ask questions whenever they encountered challenges in using the functions. The training concluded once participants felt confident in their understanding of all functions, which typically took 10 to 15 min.

The study proceeded with the three parts in sequence, using the think-aloud method. Participants were given a 10-minute break between parts. They could adjust the intensity of the electrotactile feedback at any time during the study if they felt it was too strong or weak. At the end of the study, participants participated in a semi-structured interview to provide feedback on each function and suggest improvements. The entire study lasted 2–3 h.

4.5. Data analysis

We analyzed both quantitative and qualitative data collected during the study. In **Part 1**, we calculated the average accuracy with standard deviation (SD), as well as the median and the interquartile range (IQR) of confidence ratings for recognizing map elements and route conditions. In **part 2**, we calculated the accuracy of each task with SD. In **Part 3**, we calculated the root mean squared (RMS) deviation of participants' finger movements from the predefined trajectory under trajectory guidance.

All interviews were recorded and transcribed. Two coders conducted a thematic analysis to capture BLV participants' qualitative opinions on our system and their overall experience. We adopted an open coding approach (Corbin and Strauss, 1990), initially coding the data independently and then discussing the codes during weekly research meetings. For cases with differing interpretations, we shared our perspectives and deliberated until a consensus was reached. Subsequently, we used affinity diagramming to group the codes into tentative themes, iteratively refining them until four main themes emerged. Our findings are reported according to these themes and their corresponding key codes in the next section.

5. Results

Our results included *association memory method for learning electrotactile patterns* from part 1, *maps preview task accuracy, confidence, practices, and challenges* from part 2, *deviation of trajectories* from part 3, and the *qualitative feedback on system functionalities* from all parts.

5.1. Association memory method for learning eletrotactile patterns (Part 1)

All participants (12/12) used the association memory method to memorize the electrotactile patterns for map elements and route conditions. The association memory method improved memory retention by creating associations between new information and existing knowledge or easily remembered concepts (Kohonen, 2012). The perception accuracy for map elements (98.3% with SD = 3.03%) was slightly lower than the route conditions (100% with SD = 0). The confusion matrix for participants' memorization of map elements and route conditions is shown in Fig. 8. Confidence in recognizing map elements (Md = 5, IQR = 1) was also lower than that for route conditions (Md = 7, IQR = 1). The findings in this section demonstrated the accuracy with which BLV participants recognized different map elements and route conditions on the map. The results provided the foundation for further map preview.

For map elements, all participants related the feeling of treading roads with their feet to the electrotactile stimulation on the fingertip pad. P5 noted that the pattern for POI was similar to noticing a POI with two eyes, while P11 mentioned that the water pattern felt like water flowing around her fingertip. Most participants (11/12) felt that the buildings/rooms pattern resembled a wall with a rooftop, although P11 associated it with climbing a building's stairs to its top. A few participants found recognizing greenspaces patterns inefficient, as they needed to feel the pattern multiple times to confirm its randomness. Furthermore, some participants who were less sensitive to stimulation positions struggled to distinguish greenspaces from buildings/rooms or water patterns.

Route conditions encompassed both *weather information* and *traffic information*.

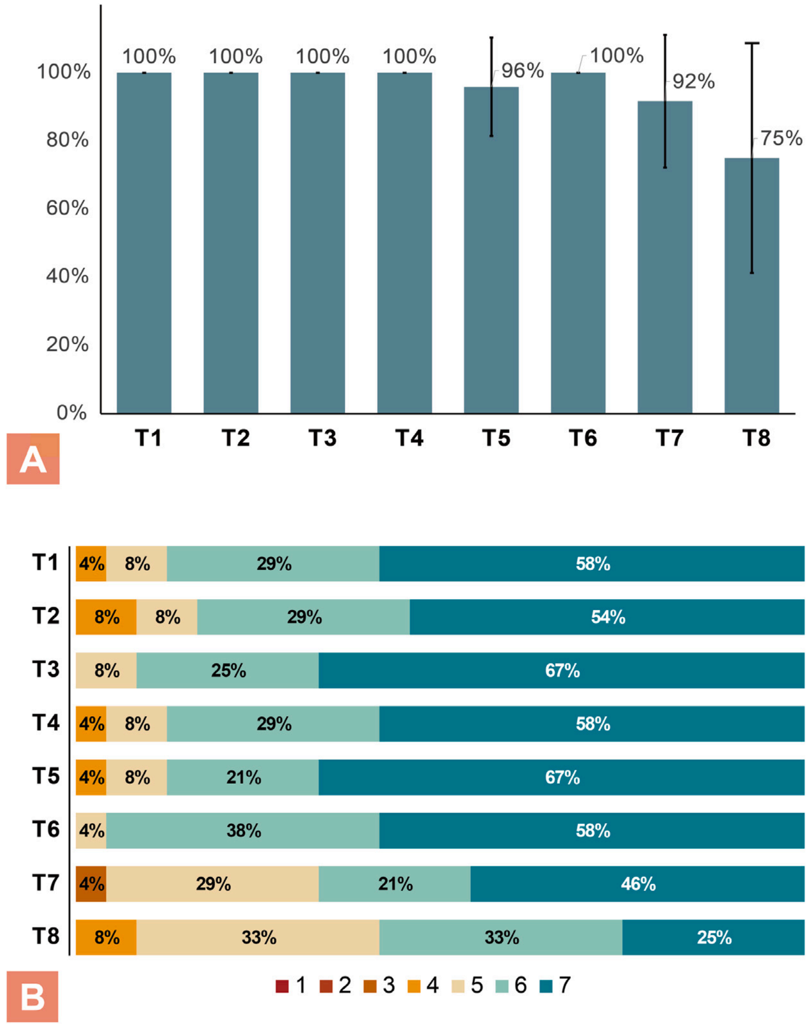

Fig. 9. Task Accuracy and Confidence in Part 2: (a) Average task accuracy (Errors bars show the standard deviation); (b) Task confidence (Likert scale ratings from 1 - Not at all confident to 7 - Extremely confident). T1 to T7 all achieved an average accuracy higher than 90%. Across each of the eight tasks, most participants rated their confidence be equal to or higher than 5.

Regarding *weather information*, nearly all participants (11/12) easily recognized and memorized the sunny pattern, associating it with sunshine from a single sun in the sky. However, P10 felt that the stimulation on the backside of the finger was not strong enough to represent sunshine and suggested adding more stimulation locations with adjustable intensity. All participants found the cloudy and rainy/snowy patterns easy to recognize. P4 appreciated the rainy/snowy pattern, as it felt like raindrops or snowflakes randomly touching their hands. Another participant noted that the simultaneous stimulation at all positions felt similar to clouds.

For *traffic information*, all participants easily recognized and memorized the traffic patterns. P4 associated the frequent whistling of vehicles during a traffic jam with high-frequency electrotactile feedback. Other participants mentioned that the stress from being in a crowded area from crowds was similar to the persistent feedback on the fingertip pad (2/11).

In sum, our findings revealed that BLV participants accurately learned the custom electrotactile patterns and successfully associated them with map elements and route conditions, providing a strong foundation using them for trip previewing.

5.2. Maps preview task accuracy, confidence, practices and challenges (Part 2)

In this section, we reported the task accuracy, confidence, preliminary strategies, and challenges from T1 to T8 in part 2, shown in Table 3. The task accuracy and confidence were shown in Fig. 9.

Task accuracy and confidence. The average accuracy for all tasks was 95% with SD = 8.8%. Most tasks achieved 100% accuracy, except for T5 (96%), T7 (92%), and T8 (75%). In T5, where participants were asked to compare the length of the lines connecting two groups of POIs, one participant incorrectly reported that both lines were of equal length. In T7, where participants examined the accuracy of a route description between two POIs, two participants mistakenly identified the route description as correct. Although P10 completed the task correctly, he reported a low confidence score of 3 out of 7. P10 explained that his uncertainty was from the two POIs' proximity, making it difficult to ensure the final POI's location. In T8, where participants were required to find the shortest route between two POIs, some participants failed to mention all the necessary roads in their route descriptions.

Preliminary strategies. We identified five preliminary strategies that participants used to complete the tasks, including *rapid exploration*, *map edge comprehension*, *POI location comprehension*, *route exploration*, and *route comparison*. For some tasks, they used a combination of preliminary strategies. *Rapid exploration* was conducted by moving their fingers rapidly across the map to understand the distribution of different map elements. They used the *map elements notification* and *location report* functions to understand the names of POIs and their relative locations. A few participants also used the *location guidance* function to revisit previously explored POIs, helping to remember those locations. This strategy helped them build a brief overview of the map.

Map edge comprehension was usually conducted after *rapid exploration*. This strategy involved participants slowly exploring the four edges of the map. They moved their finger in one direction until they could not perceive any electrotactile feedback, and identified the edge as the location where the feedback stopped. This strategy further strengthened their understanding of the map.

For the *POI location comprehension* strategy, participants began by moving their fingers at a stable speed, slower than when using *rapid exploration* strategy. Initially, they were unfamiliar with the locations of the map's edges, so they used the *map elements notification* and *location report* functions to identify the POI. They then moved their fingers from the POI directly to each of the four edges to compare distances. Unlike during *rapid exploration*, where they focused on the relative positions of different POIs, participants concentrated on determining the POI's absolute location on the map. Once they became familiar with the edges' positions, they could accurately determine the POI's location.

Route exploration was conducted by carefully exploring the roads or corridors to understand their directions and surroundings using *map elements notification* function. For MO, participants moved their fingers along the road as slowly as possible to understand its direction and POIs that were adjacent to the road. When they encountered an intersection, they switched to the other road and explored again. For MI, participants explored the POIs by moving their fingers along the corridors. They explored the edge of the corridor to understand its directions, adjacent POIs, and adjacent corridors. They moved to the other corridor once they finished exploring the current corridor. In addition, for low-vision participants, P6 reported that she could roughly differentiate the roads (black) from the buildings/rooms, which helped her memorize the routes.

Route comparison was conducted by comparing the routes from four perspectives: length, direction, reference, and endpoint location. They used *map elements notification* and *location report* functions to recognize the different POIs and roads. Some participants (P5, P9) identified incorrect routes by noting longer distances compared to their mental maps. P8 made an incorrect turn close to the endpoint, while the other (P10) identified missing landmarks along the route. Another participant (P6) identified an incorrect endpoint as it was in close proximity to the target one.

Challenges. Participants faced two main challenges when completing these tasks, including *difficulty with following the roads*, and *difficulty with memorizing routes*.

Difficulty with following the roads occurred when participants explored MO using *route exploration*. Due to the map's large scale, participants easily moved out of the roads during the exploration process. This challenge made participants more concentrated on their finger's location, and thus increased their efforts and cost them time to revise. To revise it, the participants moved back when they were out of the road.

Difficulty with memorizing routes. It was hard for the participants to memorize routes when using *Route exploration* and *Route Comparison*. Since the route consisted of several roads, they had to memorize various roads' lengths, locations, directions, and connections between roads. In addition, they had to remember the POIs' names and locations adjacent to the routes. To overcome the challenge, participants used their left hand as an anchor to mark the POIs and the street locations.

5.3. Deviation of trajectories (Part 3)

We report our findings in two perspectives: quantitative trajectory deviations and behavioral patterns in following trajectories.

5.3.1. Quantitative trajectory deviations

The average RMS distance deviations for all trials were 0.17 cm with a standard deviation (SD) of 0.08 cm, demonstrating that participants could effectively follow the guidance and comprehend the trajectories in their route preview. The trajectories were shown in Fig. 10. It demonstrated that participants could effectively follow the electrotactile guidance and comprehend the trajectories in their route preview.

We found that the average RMS distance deviations for the MO were 0.11 cm with SD = 0.06 cm, which were lower than those for the MI, at 0.22 cm with SD = 0.06 cm. The lower the RMS distance deviations, the better the participants could follow the guidance. This difference can be explained by comparing the guidance distance before turning.

5.3.2. Behavioral patterns in following trajectories

The electrotactile guidance was generated by calculating the angle between electrode groups and the intended stimulation direction. Since these angles rarely matched perfectly, participants occasionally deviated from the intended path.

Most participants followed the guidance slowly, while some moved rapidly to anticipate the next turning point. The former adopted a gradual approach, aiming to build a mental overview of the entire trajectory. As P7 described: "After the guidance, I could understand how I should walk from Central Park to Chrysler Building". The latter focused instead on memorizing turning points, believing that moving from one turning point to another was sufficient without recalling exact street or corridor names. This was similar to the strategy they reported using in real-world navigation.

Participants also developed different methods for recognizing deviations. For example, they noticed a loss of fingertip pad electrotactile feedback indicating the road pattern, or the emergence of other electrotactile patterns such as building/rooms or greenspaces. In some cases, participants detected that the guidance direction had reversed compared to the previous cue, signaling that they might have overshot a turning point.

We further observed that longer continuous segments resulted in greater deviation from the intended trajectory. In the MO maps (smaller scale), electrotactile guidance required frequent turning, which encouraged participants to follow more closely and make many directional adjustments before reaching the endpoint. In contrast, the MI maps (larger scale) involved fewer turns, causing participants to travel longer distances before each adjustment. This led to greater cumulative deviation compared to MO.

5.4. Qualitative feedback on system functionalities (All parts)

We first report key findings related to the two modes: **Map Understanding** and **Route Planning and Exploration**, then we discuss **TPA for electrotactile feedback personalization** and **difficulty with recognizing TPA hallucinations.**

Map understanding helped BLV users build two layers of mental map: *static map* and *dynamic map* Additionally, participants mentioned the necessity of *incorporating zoom-in/out and panning functions*.

The *static map* was built by understanding the names and locations of various map elements. These map elements, such as buildings/rooms and greenspaces were relatively more permanent than route conditions. Therefore, users often relied on these map elements as landmarks to build the *static map*.

The *dynamic map* was built by understanding the refreshable route conditions at different times. Since this information was temporary, users need to refresh this map regularly. For example, they could anticipate that it rains frequently in the summer or that the main avenue is crowded every day.

The interview findings showed that participants stacked *dynamic map* over the *static map*, constructing an integrated mental map. They

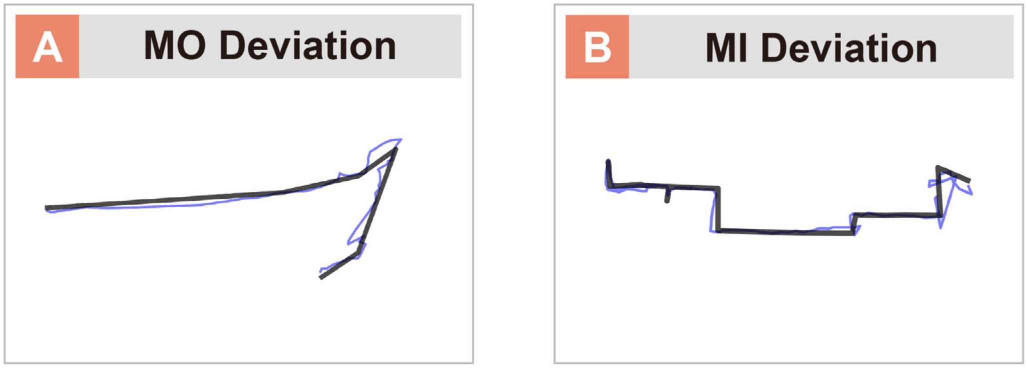

Fig. 10. Predefined Guidance Trajectory and a Participants' Movement Record Example in MO and MI. The black hard line is the predefined trajectory, and the blue thin line is the participants' movement record in (a) the Outdoor map and (b) the Indoor map.

appreciated the combination of both maps, noting that such a comprehensive understanding was rarely achievable with other haptic devices, such as refreshable braille displays or tactile graphics, as these seldom provide route conditions. In real-world scenarios, users typically had to search for this information online. As P6 mentioned, "The integrated overview broadened my understanding of my trip, allowing me to access as much information as sighted people".

Additionally, participants suggested *incorporating zoom-in/out and panning functions* to help them focus on specific areas of interest on the map. Although the current system could render maps at various scales, they believed that adding these functions would enhance their map exploration efficiency. This would allow them to access more detailed map information, such as lower-level routes and additional POIs, which would be particularly useful for potential hiking activities.

Route planning and exploration assisted BLV users in *mental trajectory building, informed route planning and confidence improvement*. Additionally, participants preferred *precsise adjustment of destinations* when using this mode.

For *mental trajectory building*, participants used electrotactile guidance to mentally map out their trajectories, including the roads, crossroads, and POIs along the way. P1 noted that "After being guided through the route, I do not need to ask others for directions because my body remembered the routes".

For *informed trip trajectory planning and confidence improvement*, the route planning and exploration mode offered an efficient trip trajectory planning experience because the TPA could select the most optimistic trajectory with the users' request. For example, they could easily add or remove one POI or several POIs simultaneously that were crowded or had bad weather, replan the trajectory accordingly, and be guided through the new trajectory. Compared to existing maps and travel apps they used, this informed travel trajectory planning improved their confidence. P3 mentioned that "The TPA considered more factors than I could when preparing trips, like the shortest trajectories, traffic, and weather conditions, which makes me confident of my journey".

Additionally, nearly all participants preferred *precise adjustment of destinations* (11/12) during route preview. P9 requested the TPA to replace all POIs that were crowded or rainy with those that were not expected to have rain or crowds during the planned time, all at once. However, most participants received traffic and weather information at different POIs and streets/corridors along the route. They then requested to exclude certain POIs or streets/corridors due to heavy traffic or rain, expressing a preference for more control over their destinations.

TPA for Electrotactile Feedback Personalization. We found that participants used the TPA to efficiently personalize the electrotactile feedback.

All participants found that the TPA could precisely understand their requests and control the electrotactile feedback accordingly. They used the TPA to personalize their electrotactile feedback in the calibration and experiment process and rarely asked the researchers for help after they learned how to make requests. For example, P2 adjusted the feedback for buildings/rooms by telling the TPA, *"the intensity is too low and it affects my differentiation from greenspace. I just want a slight increase"*. Additionally, P9 asked the TPA to stop applying electrotactile feedback for the road element, saying, *"Stop the road application. I do not want to be distracted during exploration"*.

For *higher sense of control*, compared to adjustments made by researchers, participants reported that interacting with the TPA on their own increased their sense of control over the device. Since researchers or volunteers were not always available, they usually used assistive devices independently. Except for one participant who preferred manual adjustments (P12), nearly all participants found it more convenient to ask the TPA (11/12). P5 remarked "Traditionally, I have to figure out the button's location, then understand how to use it and adjust the intensity step by step. I preferred to make more rapid and convenient personalization by asking the TPA".

Additionally, participants mainly used *fuzzy control prompts* such as "Increase the feedback" or "The feedback is too weak". They avoided precise instructions like "increase 3 V" because they could not map the voltage to the electrotactile feedback without prior experience and expertise. To prevent setting the feedback to an intolerable level, they preferred to use fuzzy prompts and let the TPA make brief adjustments. They believed that the TPA could make appropriate control and protect them from excessive stimulation.

In addition, participants adjusted the feedback provision by requesting the TPA to interpret each map element better. For example, P10 requested, "Please stop applying buildings and greenspaces; I just want to know the road networks first". He asked the TPA to disable electrotactile feedback for buildings/rooms and greenspaces during free exploration on the map, focusing only on roads. He felt that this strategy facilitated a deeper understanding of the map's road network because he could only sense and memorize the distribution and direction of the roads.

Furthermore, some participants requested that the TPA produce a specific type of electrotactile feedback described as "soft and slippery", which they felt would better replicate the grass sensation. However, the TPA was unable to generate such feedback, as there is currently no available dataset mapping LLM prompts to the corresponding electrotactile feedback.

Difficulty Recognizing TPA Hallucinations. We found that the TPA occasionally produced hallucinations, providing users with map information that did not exist. For example, the TPA suggested POIs or routes that were not actually present on the map. One possible explanation is that the TPA may have confused the real-world map with our customized map. When asked by users, the TPA might have used information from the real-world map rather than the information extracted from our map. P6 identified this hallucination when her finger was guided along a route that did not include a road he remembered existing during her free exploration.

Although most participants trusted the recommendations provided by the TPA, some expressed concerns about the difficulty of detecting when the TPA made mistakes. P1 noted that it is challenging to recognize detailed descriptions of hallucinations, which could be easily identified by sighted people through photos or street views. Specifically, active or highly detailed information, such as the location of a trash bin or the number of steps in front of a shop was hard to verify. The absence of such information could lead to inconvenience or confusion during a planned trip.

6. Discussion

We conducted a three-part user study to understand how the electrotactile patterns controlled by TPA could assist BLV participants with trip previewing. In part 1, we found that participants used the association memory method to recognize and memorize the electrotactile patterns efficiently. In part 2, we found that the electrotactile patterns controlled by TPA could assist participants in map preview. In part 3, we found that the electrotactile patterns controlled by TPA effectively helped participants preview routes. Next, we discuss the implications of the findings in four areas: electrotactile feedback customization of map comprehension patterns, map preview tasks comparison, route preview comparison, electrotactile feedback personalization prompts preferences, and supporting electrotactile pattern customization via TPA, and strategies to address incorrect responses from the TPA. We finally discuss the limitations and future work.

6.1. Electrotactile pattern customization

By empowering BLV users to design their own electrotactile patterns, we could improve their trip preview efficiency, ultimately enhancing their independence. We discuss this topic in three themes: *electrotactile feedback customization of map comprehension patterns*, *electrotactile feedback customization of guidance patterns*, and *electrotactile feedback customization for rendering 3D map icons*.

6.1.1. Electrotactile feedback customization of map comprehension patterns

Currently, we have designed all the electrotactile patterns used to convey map elements and route conditions. However, previous studies suggested that customized patterns could help BLV users more efficiently identify POIs in unfamiliar areas (Hofmann et al., 2022). Although our participants did successfully learn the pre-designed patterns using association methods, they might find it easier to remember patterns they created.

For instance, participants who were particularly sensitive to electrotactile feedback could assign different intensities to represent varying conditions of map elements. In the context of roads, they could categorize intensity levels into four tiers within an acceptable range: the higher the intensity, the higher the road level, from a trail to a highway. Additionally, participants could modify existing patterns to make them more memorable, such as by reducing the number of stimulation positions to align with their recognition abilities.

6.1.2. Electrotactile feedback customization of guidance patterns

Participants could also design their guidance patterns. For example, some suggested using different stimulation sequences to indicate directional guidance, such as sequential stimulation from one end of the fingertip edge to the other to signal turning right. One low-vision participant likened this method to a vehicle's turn signals, which they believed would be easily understood.

6.1.3. Electrotactile pattern customization for rendering 3D map icons

Our electrotactile patterns were designed to display map elements, route conditions, and route guidance within a 2D surface. However, some participants suggested that these patterns could potentially be used to render 3D models as map icons during the trip preview process. While the TPA already introduced various landmarks, prior research has mentioned the improvement of user experience when BLV users interact with 3D icons (Hofmann et al., 2022; Nagassa et al., 2023). As a result, though it was hard to fully mimic the sensation of touching 3D icons, exploring the possibility of using electrotactile feedback to display customized 3D models might enhance the trip preview experience for BLV people. This direction offered an intriguing opportunity for future investigation.

6.2. Map preview tasks comparison

We compared our results in part 2 with prior works, focusing on *landmarks*, *spaces*, and *routes* task groups. Prior work has explored how BLV people perform non-visual navigation in different scenarios, such as on touch surfaces (Guerreiro et al., 2015, 2020) and in public spaces (Asakawa et al., 2019; Guerreiro et al., 2018, 2019). These studies revealed diverse strategies that BLV people employ to navigate effectively in both digital and real-world environments.

6.2.1. Landmarks

The work most closely related to ours was by Brock et al. (2015) and Guerreiro et al. (2015). Brock et al. compared the effectiveness of an interactive map (providing both tactile and audio feedback) with traditional tactile maps (providing tactile feedback only). Guerreiro et al. explored the BLV people's exploration strategies when interacting with a tabletop (Guerreiro et al., 2015).

Brock et al.'s study employed the same three task categories as ours: landmarks, spaces, and routes. Participants in our study achieved an average accuracy of 100% in landmarks, surpassing their results, which reported 83.3% for the interactive map and 85% for the tactile map (Brock et al., 2015). One factor contributing to this high accuracy could be that participants easily received landmark names and details from the TPA. Compared to the interactive map, the TPA provided brief introductions in addition to names, helping them memorize POIs. Compared with tactile maps, BLV users did not need to recognize the braille or tactile shapes to understand the landmarks, which was a slower process requiring higher levels of interpretation compared to simply asking the TPA.

In addition, Guerreiro et al. reported exploration strategies among BLV participants that were similar to those observed in our user study (Guerreiro et al., 2015). For example, their identified *freeform* strategy resembles our participants' *rapid exploration*, where users moved erratically and without a clear pattern to gain an overall sense of the surface. In our study, participants similarly conducted rapid movements across the map to grasp the distribution of different elements. One difference was that Guerreiro et al. identified two-hand exploration strategies, which were not observed in our study due to the constraints of our fingertip device. Building on this, future work could investigate the potential of two-hand strategies to further enrich non-visual map exploration.

6.2.2. Spaces

The *spaces* task groups were relevant to those from Brock et al.'s work (Brock et al., 2015), Nagassa et al.'s work (Nagassa et al., 2023), and Guerreiro et al.'s work (Guerreiro et al., 2015). Nagassa developed three types of 3D-printed indoor tactile maps and asked participants to conduct a series of tasks similar to our *spaces* and *routes* tasks groups. For example, the task *"You are facing a... What is the relative direction of b?"* was similar to T4, where participants needed to indicate the direction of two POIs' connecting line.

Our participants achieved an average accuracy of 99%, higher than the 62.5% (Griffin et al., 2020) and 84% (Nagassa et al., 2023) reported in prior studies. This might be attributed to participants' ability to build a comprehensive understanding of the map through various preliminary strategies, such as *rapid exploration*, *map edge comprehension*, and *POI location comprehension* (Section 5.2). Repetition of these strategies might deepen their mental maps, enabling more accurate task completion.

When comparing our findings with Guerreiro et al.'s *focused* strategy, we identified a similar yet distinct approach that we termed the *POI location comprehension* strategy. Both strategies were used to determine the exact location of a target or map element. In our study, participants located a POI's absolute position by moving their fingers from the POI outward to each of the four edges of the map to compare distances. In contrast, Guerreiro et al. reported that participants first navigated to the area where they recalled hearing the target, then repeatedly traced small, overlapping movements within that region. If unsuccessful, they gradually expanded the search area until the target was found (Guerreiro et al., 2015). Future research is needed to investigate the underlying reasons for this discrepancy and to explore other strategies.

6.2.3. Routes

Similar to *spaces*, we compared the *routes* with Brock et al.'s work (Brock et al., 2015), Nagassa et al.'s work (Nagassa et al., 2023), and Guerreiro et al.'s work (Guerreiro et al., 2015).

Participants reached an average accuracy of 89%, slightly higher than the 66.7% (Griffin et al., 2020) and 72% (Nagassa et al., 2023) reported in previous studies. This improvement might stem from their detailed understanding of both maps and routes, developed through strategies like *route exploration* and *route comparison*. With these preliminary strategies, participants could build or recognize a route based on multiple explorations of surrounding roads and a comprehensive map understanding.

In addition, unlike prior works where *routes* accuracy exceeded *spaces* accuracy, our findings showed the opposite. This difference might be due to the tactile maps in prior studies having raised lines that made following roads straightforward. In contrast, participants in our study had to rely on landscape feature patterns, which some found challenging when following the roads, leading to occasional errors.

Our *route exploration* and *route comparison* strategies shared fewer similarities with Guerreiro et al.'s strategies, such as *path scan*. This difference primarily stemmed from the design of the exploration environments. In our study, participants explored structured maps, where they were required to follow and remember roads or corridors to complete the tasks. By contrast, Guerreiro et al.'s participants were allowed to freely explore the entire surface without being constrained by predefined map layouts.

6.3. Route preview comparison

We discussed the route preview comparison from two perspectives: **two-step short-distance route preview** and **route preview prompts preferences.**

6.3.1. Two-step short-distance route preview

Our electrotactile patterns played a crucial role in helping BLV users construct both a mental map and a mental route. They utilized it to comprehend the distribution of various map elements and route conditions, followed by electrotactile guidance to understand the directions and roads to take. These steps were further enhanced by the TPA, which allowed BLV participants to easily access POI details, select destinations, and create trip trajectories through simple audio interactions, minimizing the need for multiple operations. The TPA effectively bridged the gap between BLV users and the device, making the entire process faster and more efficient.

6.3.2. Route preview prompts preferences

BLV participants exhibited different preferences when using prompts to interact with the TPA.

For map and route preview, participants primarily inquired about POI details and added or removed POIs from their trip trajectories. They tended to use precise prompts, such as "Tell me about the building's history" and "Remove the New York Exchange from my plan". These specific questions reflected their understanding of landmarks and particular interests. Knowing what they wanted to explore allowed them to articulate their inquiries clearly.

6.4. Electrotactile feedback personalization prompts preferences

For electrotactile feedback personalization, participants preferred using fuzzy prompts, such as "Lower the voltage" or "The feedback is not clear". They opted for these less specific prompts because they were unfamiliar with the required intensity levels and left it to the TPA to control the feedback.

In contrast, prior studies have shown that BLV people usually use precise prompts to make requests, such as "Can you describe the environment around?", "Where can I find peanuts?", and "Could you please tell me what the instruction manual says?" during travel and shopping scenarios (He et al., 2024; Yang et al., 2024). These precise prompts stemmed from their familiarity with their needs based on past experiences. However, when dealing with devices or techniques they were less familiar with or that might pose safety concerns, they tended to use broader, more cautious prompts to avoid discomfort with electrotactile feedback, such as possible itch or slight pain.

6.5. Supporting electrotactile pattern customization via TPA

BLV users could customize their electrotactile patterns through the TPA, as designing such patterns via visual interfaces presents challenges. Currently, TPA allows users to adjust the intensity and select from predefined patterns, but there is a need for further exploration in developing a dataset that maps LLM prompts to the corresponding electrotactile feedback. For instance, people often describe the same haptic sensation with different terms, such as "sharp" and "acute", or "graceful" and "smooth" (Hornecker et al., 2023). The TPA should discern these subtle differences and similarities in language and generate the appropriate electrotactile feedback.

Moreover, even identical haptic sensations, such as "hard like a stone"—can be produced by different types of haptic feedback, which may necessitate distinct parameters. For example, vibration relies on adjustments to amplitude and frequency, while electrotactile feedback requires variations in signal types and current levels (Lin et al., 2022). To accurately replicate the sensation, the TPA must consider the specific types of haptic feedback and the differences in their control parameters.

6.6. Strategies to address incorrect responses from the TPA

Our study showed that it is essential to support BLV users by easily validating the correctness of information provided by the TPA. Currently, BLV people employ various strategies to understand AI errors, including experimenting in low-risk and familiar settings, leveraging non-visual sensemaking skills, collaborating with sighted bystanders or community members, and cross-referencing multiple technologies and applications (Alharbi et al., 2024; Gonzalez Penuela et al., 2024; Adnin and Das, 2024). They also compared explanations from different devices or sources, such as AI tools and Google, to identify potential errors (Adnin and Das, 2024). Based on these findings, the TPA could be enhanced with additional functions to facilitate easier error verification. For example, users could directly request images or descriptions from the TPA to help validate its outputs.

In addition, incorporating third-party evaluation methods, such as crowd-sourced validation, could further enhance the accuracy of information provided. Prior works have also noted that BLV users often ask sighted people to help verify AI errors (Adnin and Das, 2024; Alharbi et al., 2024). These validation mechanisms should be integrated into the TPA, enabling users to cross-check information in real time.

Moreover, sourcing data from official information channels and providing references would improve the reliability of the TPA's responses. This approach would empower users to independently verify information using authoritative resources. Such a function aligns with BLV users' strategy of cross-referencing information across different technologies and applications (Alharbi et al., 2024).

Finally, providing users with the reasoning process behind the TPA's response could increase transparency. By understanding the logic behind the information, users can assess whether the conclusions were drawn appropriately and decide whether to trust the given information.

6.7. Limitations and future work

In this section, we discussed the limitations of our current work and outlined potential future directions, including the addition of **multi-layer maps**, enabling users to preview **hierarchical routes on adjustable map scales**, and **combination use with real-time navigation systems**.

Incorporating **multi-layer maps** could benefit BLV users when navigating complex environments such as urban areas and mountains. Prior research has highlighted the usefulness of multi-layer maps in helping BLV users understand multi-story buildings like shopping malls (Nagassa et al., 2023). Urban areas often consist of multiple buildings with several floors, requiring visitors to navigate elevators or stairs to reach various offices, classrooms, and shops. Similarly, mountains have significant elevation changes, with POIs connected by stairs or slopes that span different heights. By splitting POIs into different map layers based on their altitudes, we could help users build more accurate 3D representations of mountainous terrain. Therefore, to enhance the travel experience in both urban and mountainous areas, it was crucial to provide BLV users with multi-layer maps.

Allowing users to preview **hierarchical routes with adjustable map scales** could further support their overall trip preview. Currently, our device supports only one map scale at a time. However, participants could better preview routes with adjustable scales. For instance, when visiting multiple areas within a city, users could first preview the main routes connecting these areas. Then, within each area, they could preview secondary routes to explore different POIs. This approach would enable a more detailed and personalized route preview, offering finer control and a better travel experience for BLV users.

The **combination use with real-time navigation systems** might enhance the travel experience for BLV users. Currently, participants rely on real-time navigation devices to follow routes in journey but often miss noticing the surrounding POIs. Like sighted people, if BLV users were aware of nearby shops or restrooms along their route, they could choose to visit these locations and then easily return to their path. This would likely result in a smoother and more comfortable travel experience.

While our study utilized Likert scale questions on the confidence for completing a task, the **use of additional standardized post-test questionnaires**, such as the After Scenario Questionnaire (ASQ), System Usability Scale (SUS), Questionnaire for User Interaction Satisfaction (QUIS), and NASA Task Load Index (NASA-TLX) could help us better interpret qualitative data, including the effort required for different tasks. Future work can incorporate these scales for more structured user feedback and data analysis.

7. Conclusion

In conclusion, we conducted a three-part user study to evaluate how the LLM-powered trip previewer might assist BLV people in map and route preview. In part 1, participants successfully recognized and memorized electrotactile patterns for the map elements and route conditions using the association memory method. Parts 2 and 3 showed that the LLM-powered trip preview assistant effectively assisted participants in map and route preview. Then, we elaborated on electrotactile pattern customization, map preview tasks and route preview comparison, route preview prompts preferences, electrotactile feedback personalization prompts preferences, electrotactile pattern customization via TPA, and strategies to address incorrect responses from the TPA. Our work highlights promising future directions for LLM-integrated electrotactile assistive tools to enhance map and route preview for BLV users.

CRediT authorship contribution statement

Chutian Jiang: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yinan Fan:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Methodology, Conceptualization. **Junan Xie:** Writing – original draft, Conceptualization, Visualization, Investigation, Methodology. **Emily Kuang:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis. **Kaihao Zhang:** Writing – review & editing, Supervision. **Mingming Fan:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work is partially supported by Guangdong Provincial Key Lab of Integrated Communication, Sensing and Computation for Ubiquitous Internet of Things (No. 2023B1212010007), Guangzhou-HKUST(GZ) Joint Funding Project (No. 2024A03J0617), Guangzhou Higher Education Teaching Quality and Teaching Reform Project (No. 2024YBJG070).

Appendix

A.1. Prompts used for TPA

This section introduces the specific prompts utilized in our TPA system, including prompts for the *overarching control agent*, the *trajectory planning agent*, and the *electrotactile personalization agent*.

A.1.1. Prompts for overarching control agent

You are an overarching control agent for a trip preview system. Your task is to interpret the user's instructions and accurately determine their requirements. The user's requirements may fall into one of the following categories:

1. Modifying the trip plan. This includes changes to the destinations or requests for information about specific landmarks.

2. Adjusting the electrotactile feedback. This involves modifying the intensity of the voltage at landmarks, as requested by the user.

3. No specific requirement. This indicates that the user has no actionable request at the moment.

Here is the user's instruction: {instruction}.

Table 4
Technical evaluation results: The results examples show the trip preview assistant's control results of electrotactile feedback. P4-6 means simultaneous application of P4, P5, and P6. P4 to P6 means sequential application of P4 and P6, which conveys direction cues.

Electrotactile features	Control mode	Control details	Prompts examples	Results examples	Accuracy
Stimulation Position	Fuzzy	Point (difference)	adjust to a point with lower/higher number	from 5 V to 2 V, 4 V/ 8 V, 7 V	20/20
		Area (difference)	adjust to an area with lower/higher points number, Widen/narrow the area	from P4-6 to P1-3/P6-8, from P4-6 to P2-8/P5	40/40
		Point (target)	apply on a point on the left/right/top	from P5 to P2, P3/P7, P9/P5, P6	30/30
		Area (target)	apply in the area on the left/right/top	from P4-6 to P1-3/P7-9/p5–6	30/30
	Accurate	Point (difference)	adjust to a point with one number lower/higher	from P5 to P4/P6	20/20
		Area (difference)	adjust to an area whose central point is with 1 number lower/higher, adjust to an area with two fewer/more numbers	from P4-6 to P3-5/P5-7, from P3-7 to P4-6/P2–8	40/40
		Point (target)	apply to point 3/5/8	from P5 to P3/P5/P8	30/30
		Area (target)	apply to area (2,3,4), (5,6,7), (7,8,9)	from P4-6 to P2-4, P5-7, P7–9	30/30
Stimulation Direction	Fuzzy	Precise (difference)	turn left/right slightly	from 78° (P1 to P4) to 84° (P1 to P3)/ 68° (P3 to P4)	19/20
		Vague (difference)	turn left/right largely	from 78° (P1 to P4) to 106° (P9 to P7)/ 49° (P2 to P6)	20/20
		Cardinal (target)	turn to left/right/forward/backward	from 78° (P1 to P4) to 180° (P7 to P4)/ 1° (P4 to P7)/ 90° (P10 to P9)/ 270° (P9 to P10)	40/40
		Ordinal (target)	turn to bottom-left-top-right /top-left-bottom-right/bottom-right-top-left/top-right-bottom-left	from 78° (P1 to P4) to 41° (P1 to P7)/ 317° (P4 to P10)/ 137° (P10 to P4)/221° (P7 to P1)	40/40
	Accurate	Precise (difference)	turn left/right 15°	from 78° (P1 to P4) to 95° (P10 to P8)/ 62° (P2 to P5)	20/20
		Vague (difference)	turn left/right 30°	from 78° (P1 to P4) to 106° (P9 to P7)/ 49° (P2 to P6)	20/20
		Cardinal (target)	turn to 0°, 90°, 180°, 270°	from 78° (P1 to P4) to 1° (P4 to P7)/ 90° (P10 to P9)/181° (P7 to P4)/270° (P9 to P10)	40/40
		Ordinal (target)	turn to 45°, 135°, 225°, 315°	from 78° (P1 to P4) to 41° (P1 to P7)/ 137° (P10 to P4)/221° (P7 to P1)/317° (P4 to P10)	40/40
Stimulation Intensity	Fuzzy	Precise (difference)	increase/decrease some intensity	from 10 V to 12 V, 11 V /8 V, 7 V	20/20
		Vague (difference)	increase/decrease more intensity	from 10 V to 14 V, 13 V /7 V, 5 V	20/20
		General (target)	adjust to a medium/large/low intensity	from 10V to 14 V/21 V/8 V	30/30
	Accurate	Precise (difference)	increase/decrease 1 V	from 10 V to 11 V/9 V	20/20
		Vague (difference)	increase/decrease 5 V	from 10 V to 15 V/5 V	20/20
		General (target)	adjust to 1 V/5 V	from 10 V to 1 V/5 V	20/20
Electrotactile Feedback Induction	Mixed Induction	Mixed Induction	induce an electrotactile feedback on point 5 with 10 V	P5, 10 V	10/10
			induce an electrotactile feedback on point 8 with a large intensity	P8, 20 V	10/10
			induce an electrotactile feedback on the right with 15 V	P7-9, 15 V	10/10
			induce an electrotactile feedback on the top with a low intensity	P5-6, 10 V	10/10
			induce an electrotactile feedback turn to left with 10 V	P7 to P4, 10 V	10/10
			induce an electrotactile feedback turn to left with a middle intensity	P4 to P7, 15 V	10/10
			induce an electrotactile feedback turn to bottom-right-top-left with 20 V	P10 to P4, 20 V	9/10
			induce an electrotactile feedback turn to bottom-right-top-left with a low intensity	P4 to P10, 10 V	9/10

A.1.2. Prompts for trajectory planning agent

You are a trajectory planning agent for a trip preview system. Here are the names of the landmarks in this map: {mapInfo}. Your task is to introduce the user to the map based on these landmarks and determine the user's points of interest. Please note that you can only provide information about the landmarks mentioned above.

There are four types of system modes for trajectory planning:

1. **Landmark Query:** Activated when the user asks for information about the landmarks in their current location.
2. **Weather:** Activated when the user asks for weather information in their current location.
3. **Traffic:** Activated when the user asks for traffic information in their current location.
4. **Default:** Activated when the user does not request to switch modes.

After several rounds of communication with the user, you record the landmarks the user is interested in based on your {memory}.

The content appearing in {memory} are updated for each participant.

Your next task is to determine the appropriate mode to be displayed by combining the recorded {memory} with the user's current instruction: {instruction}.

A.1.3. Prompts for electrotactile personalization agent

You are an electrotactile personalization agent. Your task is to adjust voltage based on the user's instruction: {instruction}.

Define the voltage levels as follows:

1. **Suitable voltage levels:** 13, 14, 15, 16, and 17.
2. **Low voltage levels:** 8, 9, 10, 11, and 12.

3. High voltage levels: 18, 19, 20, 21, and 22.

You should operate in two steps: **generate observations and thoughts** and **perform actions**

Generate Observations and Thoughts includes *observation* and *thought*.

For *Observation*, you should briefly describe the user's instruction based on {instruction}. If the instruction is not in the local language, treat it as noise. If the user's instruction contains information about the current electrode and strength, describe it.

For *Thought*, you need to determine what actions to be taken to fulfill the instruction based on the *observation*. If the user command specifies an electrode and strength, calculate the target voltage or adjust the current voltage accordingly. If the instruction is unclear or fuzzy, increase or decrease the voltage randomly by 1–2 V or 3–4 V, depending on the degree of ambiguity.

During **Perform Actions**, you need to perform *Adjust Voltage* or *No Change* based on the *thought*:

For *Adjust Voltage*, you should output the target voltage based on the strength specified by the user. Ensure the voltage remains between 0 V and 36 V.

For *No Change* You need to keep the voltage unchanged.

A.2. Semi-structured interview questions

a. How has our device facilitated your understanding of these maps in the study?

b. Which functions are most and least useful for understanding maps, and why?

c. How did you find the GPT-generated electrotactile feedback?

d. How would you evaluate the interaction method that combines voice and GPT (e.g., speaking the desired destination, automatic route planning, changing the route via voice, and automatic navigation)?

e. How has our device impacted your ability to make plans? Which functions assisted you in planning a trip?

f. What are your suggestions for improving each function?

g. What are your suggestions for improving the device as a whole?

h. Do you have any other comments or suggestions about the device?

i. In which other scenarios do you think our electrotactile directional indication technology could be applied?

Data availability

No data was used for the research described in the article.

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