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Influences of different underground station map designs on map-reading and wayfinding

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Abstract
Map-reading and wayfinding form one continuous and indivisible process; however, numerous studies have only focused on one of the two. This study focused on the relationship between map-reading and wayfinding to understand how map users read and acquire information from maps. Thirty Participants were divided into three groups of ten on Shibuya Station in Tokyo. The first group used mounted maps, the second group used a printed handheld copy of the station map, and the third group used a digital map provided by Ekipedia. All participants were allocated the same starting point and destination, and were required to perform map-reading and wayfinding to the destination as well as fill out an evaluation questionnaire. The results showed that the absolute accuracy scores (AASs) of digital-map users were far lower than those of handheld map users. The number of landmarks mentioned in the route planning of different map types and number of stopping times during the wayfinding process were significantly correlated. Digital-map users had the highest frequency of landmark use and longest map-reading times, but the shortest stopping times when wayfinding. The task results indicated that digital users had the lowest errors among the three groups; however, the evaluation questionnaire suggested that participants considered digital maps to be the least effective. Seemingly easy-to-understand maps might not be reflected in participants' wayfinding behavior. Overall, this study suggested that only the successful matching of maps with the actual environment can enable successful wayfinding and create useful spatial knowledge.

Keywords Map design · Map-reading · Wayfinding · Route description

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1 Introduction

An underground station is a large underground space and a node in the mass public transportation system. Numerous passengers enter underground stations to depart for their destinations. Such a transportation system consists of several complex routes and generally have several underground floors that mainly consist of platforms, passageways, and stairs. Designers plan gates, stairs, ticket vending machines, toilets, lockers, information centers, and stores for the convenience of passengers. Compared with spaces above ground, underground artificial environments have relatively few recognizable spatial features and landmarks and their spaces look similar or lack signage; thus, individuals can easily lose their direction. Therefore, developing a highly effective wayfinding method for underground stations has become a popular topic in the field of design. Regardless of the type of map used, signages are the most frequently used landmark for people to find their way. Therefore, the designers of these signages and map designers should unify their content for each signage. Specifically, these signages must appear in maps as they do in the actual environment. Only then can map users determine their direction by matching maps with the actual environment, and thus make correct wayfinding decisions.

The whole process of using a map and walking toward a destination can be divided into two parts: map-reading and wayfinding. Passini [1] indicated the three operations characterizing that type of map-reading can be summarized as: 1)to identify one's position and to establish the spatial relation between the map and the physical reality of the setting; 2)to find informational leading to the location of destination on the map; 3)to figure out a route and to memorize the decision plan necessary to its execution. Among communication models, Koláčný [2] indicated the process from map-maker's encoding to map-user's decoding. Map makers take the trouble of translating geographic reality into cartographic symbols, because maps are the most effective and efficient way of transferring data to users and of providing insight into, and an overview of, these data [3]. To convey particular spatial information, makers create a map based on their cognized reality mixed with their professional knowledge and cartographic rules. Map readers then derive specific information based on their needs via cartographic rules and prior knowledge, forming another type of reality they recognize. Eventually, these two types of reality might differ. Map-reading studies have shown that after users read a map, they construct a cognitive map; however, differences exist between users' perceived image and that of the map makers [2, 4], and such differences must be investigated. Orientation is a type of behavior employed to solve spatial problems. Wayfinding decisions involve map users matching the actual environment with their perceived map. Understanding how map users find their direction using their cognitive map is crucial, and this is particularly true when they are using different types of map.

This study considered the diversity of passengers and their wayfinding needs under various situations. People's wayfinding process in an underground station differs from their usual wayfinding method. For example, ticket gates and barriers limit the scope and directions in which passengers can move about, thereby influencing their movement. Passengers can only pass through gates to enter or exit the station; therefore, how such gates are presented on maps will influence the smoothness of movements in and out.

For example, stairs in a building are usually in the same location on each floor, and thus people can move up or down to other floors; they only need to search for a stairway on the floor they are on and descend to reach the ground floor. Therefore, the maps of most buildings are two-dimensional. However, in underground stations, the location of stairs on each floor differs and passengers must usually spend time walking on each floor to reach them. They must use two types of routes to reach their destination, namely vertical and horizontal, which is far more complex than in ordinary buildings.

The provision of spatial information enables underground transport users to enjoy a highly effective wayfinding service. Every underground station has maps, but their usage rate is low, and hence they might be easily ignored. Different to directional signs, maps provide knowledge on space measurements, indicating that the amount and content of information provided by maps have different effects on wayfinding. Reconsidering the effects and functions of maps is a topic that requires considerable attention. This is particularly true for public designs where needs of different users must be supported. This study focused on the relationship between map-reading and wayfinding to understand how users read and obtain information from different kind of maps, including mounted maps inside underground stations, paper maps, and digital maps on smartphones, as well as possible misunderstandings and confusion that spatial information provided by maps may cause. This included how users reach their destinations through the help of maps and potential problems that may occur during their wayfinding process. In addition, the researchers sought to understand and compare users' map-reading and their actual displacement, as well as missed information and the reasons for it. This empirical study aimed to design a map that was easy for users to use and understand; its findings can serve as a reference for future map designs.

2 Related works

An underground station is a public space and its purpose is to provide services to varying numbers of passengers. Various types of wayfinding method must be considered when designing and planning underground stations. One study on orientation suggested that individual differences in factors such as sex, cultural background, familiarity with an environment, experience, and spatial ability influence people's orienting behavior [5]. For example, commuters would choose a fixed route according to their personal experiences, whereas first-time travelers would search step by step according to their initial wayfinding plan. Designers design spatial information such as maps and directional signs to assist passengers in reaching their destinations regardless of whether they are familiar with their surrounding environment.

There is significant evidence that maps are a mental aid to navigation. Numerous environmental and spatial cognition studies have examined how maps work in the mind, and it is accepted that maps help people to create o a spatial mental model as a "cognitive map." Maps can help passenger locate where they are, construct a cognitive map, and build spatial knowledge. Although passengers use directional signs more frequently than maps, directional signs and maps play different roles in self-orientation. Research on wayfinding is increasing gradually with advancements in building technology and upscaling of indoor spaces. The map is often held basically to be a means of communication [4]; the map-maker is attempting to communicate information to the map-user [6]. Morrison [7] thought that selecting, categorization and simplification of map symbols are three cognitive displays of cartographers, and the interpretation of maps needs to be constructed by readers' prior knowledge mixed with the cognition generated during map-reading. The process of examining a map generates some image in the mind of the viewer. As map designers, we hope that this image is a reasonable approximation of the data sample (which was used in making the map) and, by extension, of the real world from which the sample was derived. There are, however, a number of variables which act to prevent this image from being the replica we desire; symbolically, the variable resistance represents this loss or imperfection, one which may change from task to task [8]. Maceachren [9] proposed that, when our vision are processing maps, we will firstly start from those marginal or discontinuous regions on the map and then further do visual description and arrangement in terms of size, depth, brightness among different symbols. Secondly, on a higher level, we will evaluate what we have acquired in the previous steps. At this moment under the knowledge schema, the visual description then transmits, questions, and adjusts with knowledge in long-term memory, deriving certain meaning from maps. That is, via the visual cognition, information is being recreated, and redefined again and once more. Therefore, a model is continually developed through the processes of reading, understanding, and modifying maps into actions.

Pocock's [10] model was an elaboration of the proposal put forward by Downs. It was divided into three main sections, each consisting of inter-related components. The first section was the environment and comprised three sets of stimuli: previous information, present context, and the actual environment. The selection from these sources influenced the information reaching the second, perceiver, stage, which included four sets of factors: basic physiological make-up, basic psychological organization, cultural characteristics, and the current state of the individual. These factors, in combination, acted as filters-selecting which aspects of received information were processed-and the output from this processing contributed to the 'image' [11].

Observations of map-reading behavior exhibited by the wayfinding subjects as well as their assessment of the maps encountered will again constitute the basic data for discussion [1]. Golledge [12] mentioned SIRN (Synergetics inter-representational network) model, internal input and external input. As long as input occurs, new output is produced, and decisions are then influenced. Hence, the opportunity to read maps and the form, the quantity, the location of maps will impact on decision-making. Golledge [12] suggested that maps can be used to measure spatial knowledge. For example, travelers can use maps to plan their routes and walk to their destination. Maps also provide knowledge on space measurements and enhance users' understanding of their surrounding environment. Furthermore, they can obtain navigation knowledge and form a cognitive map in their mind that enables them to find their direction. Making maps consisted mainly of first gathering the precious geographic data and then applying expertise to visualize these data. In visualizing the data, important choices had to be made. The most important of these was how to represent the originally spatial, spheroidal information on the flat surface.

Fujimori et al. [13] shows cartographers also make use of points, lines, and areas to illustrate the spatial relationships. These spatial relationships are divided into four types: Connectivity, Near, Intersection, and Containment. Hence, cartographers make use of these symbols (point, line, area) to display objects in the real world and further show the spatial relation between these objects by reflecting the relation within these symbols on the map. Cartographers describe the 3D space on a 2D map by "symbols". Generally speaking, cartographer make use of visual variables, which include size, hue(color), value, texture, orientation, and shape to show the difference among symbols [14]. Landmarks usually act as anchor points for organizing other spatial information into a layout. Landmarks also act as organizing features in a wayfinding context [12]. Judging from landmark-checking, we can know where we need to turn. Landmark-checking also helps us identify where we are and whether we are on-route or not. People rely on a variety of architectural cues (atriums, elevators, variations in floor, and wall color, visual access to outside landmarks, plan configuration, etc.) to find their way through buildings. These architectural features form a system of landmarks [15] and should therefore be included in the list of items that need to be considered when encoding diagrams [16].

Nelson [17] took map with two variables to conduct experiments, finding that having a notable bottom-shaping and a vivid color contrast is an important technique; too much symbols or colors would prolong the time for cognizing, and a low degree of similarity in symbols would then shorten it. The proposed methods are applied to the assessment of four commonly used visual variables for designing 2D maps: size, color value, color hue, and orientation. The empirical results suggest that the visual variable size is the most efficient (fastest) and most effective (accurate) visual variable to detect change under flicker conditions [18]. Tang et al. [16] in evacuation diagrams study indicated the relationship between diagrams and reading interpretation. This communication process consists of encoding and decoding steps. This communication process consists of encoding and decoding steps. Encoding can be done in the form of architectural floor plans, but the diagrams need to have commonalities such as "convention and use" and "explicit agreement" in John Fiske's [19] communication theory.

People view maps as effective and desirable sources of information when traveling to new destinations [20]. For passengers, finding their way inside the indoor space is the most important consideration for optimizing their experience [21]. Map was found to significantly reduce backtracking in a hospital setting [22]. Maps also have proven to be effective in other ways. Subjects who used a schematic map were able to find the most efficient routes to a destination [23], and handout maps in museums were able to successfully orientate visitors [24].

Individual difference is a common viewpoint of map designstudies as wayfinding performance or the individual wayfinding strategy. Passini [25] selected hospitals as an example for their wayfinding experiments and found that most patients had problems decoding symbols and abbreviations on graphic displays. Hölscher et al. [26] investigated horizontal and vertical wayfinding strategies in several buildings, and Lawton [27] examined indoor and outdoor wayfinding strategies. Later studies have focused on comparing the efficiency of different types of markers. Some studies have used virtual environments to examine wayfinding situations in the real world; however, spatial knowledge transfer depends on numerous factors, and such designs may be counterproductive [28]. Regarding wayfinding information, O'Neill [15] suggested that using a floor plan to conduct wayfinding was far less efficient than using landmarks in a complex indoor space. Zheng found that 2D map subjects' wayfinding performance was superior to that of 3D map subjects. 2D map subjects had problems with stairway connections, but 3D map subjects were confused by the incompleteness of symbols. 2D map subjects used wall and action-based information to construct their route knowledge, but 3D map subjects tended to rely on landmarks. [29]

These studies are to understand the difference between map makers and map users. Ottosson [6] observed that experiments featuring map-reading and wayfinding required real in-depth investigations.

Maps are not equally helpful to all travelers, because map reading is an acquired skill that varies in the population [30, 31] In terms of user behavior, map-reading and wayfinding form a continuous and indivisible process, yet most studies have only focused one of the two. Scant studies have focused on the effectiveness of underground station maps. A printed, paper maps can indeed assist visitors in finding their way through complex buildings, but that there are limitations to their ability to overcome architectural barriers [32]. We have no idea about what kinds of maps might be more effective or cause different wayfinding problems. Therefore, this study focused on the relationship between map-reading and wayfinding to understand how users read and obtain information from different kinds of maps, as well as possible misunderstandings and confusion that spatial information provided by different maps may cause.

3 Method

To understand how maps can help wayfinders reach their destination, the present investigation was divided into three parts: map-reading, actual wayfinding, and an evaluation questionnaire. The objective was threefold: to gain knowledge of (1) how wayfinders plan their routes after reading maps; (2) how they use maps and markers of the surrounding environment to aid the wayfinding process; and (3) their evaluation of the maps after they completed the wayfinding task. Three types of commonly seen underground maps exist: mounted maps inside underground stations, paper maps, and digital maps on smartphones. Because users of each encounter different problems, this study compared the three map types. The opportunity to read map is divided into three categories in this study, (1) read the map at the starting point and then walk to the goal without reading again. For example: in subway evacuation, one cannot read the map one more due to the limitation of the eyesight or current surroundings. (2) read the map at the starting point and then read again at some specific locations en route (e.g., the mounted map on the wall). (3) read the map anytime anywhere from the starting point to the goal (e.g., the paper map, and the digital map on mobiles).

The researchers focused their investigation on Shibuya Station in Tokyo. It is one of the busiest stations in Japan, with hundreds of thousands of commuters passing through each day. The researchers recruited 30 participants and divided them into three groups of 10 participants. Among the participants, 15 were men, 15 were women, and their average age was 22.8 years. They were all overseas students who had stayed in Japan for less than 3 months and this was their first time in Shibuya Station. The first group read the station's mounted maps (Fig. 1). The second group used the paper version of the station map from the JR official website (Fig. 2). The third group used a digital map of the station provided by ekipedia (Fig. 3). All participants were allocated the same starting point and goal. The investigation had three parts: map-reading, wayfinding, and an evaluation questionnaire.

The size of the mounted map was 160 × 160 cm and the map featured a You-are-here (YAH) symbol. Additionally, the view angle of the map was determined by the actual location where the map was positioned. The map was a 3D perspective image. Orange lines were used on the map to distinguish and connect with stairs and escalators at different floors.The size of the paper map was 29.7 × 21 cm and it was a printable version of the Shibuya Station map from the official website of a station operator. The sample map was a typical perspective drawing printed on A4-size paper and YAH information was not provided anywhere. Participants held the map when performing the wayfinding task.The digital map was installed on a smartphone with a 4-in. screen and provided by the Japanese Underground Station app found on the Apple App Store. The digital map was drawn to be two-and-a-half-dimensional (2.5D), but no orientation service was provided in the underground space. Consequently, no YAH information was provided, and participants had to locate themselves unaided.

All participants' destination was designated as locker B on the B1 floor. No signage exists in the routes for the participants to locate their goal. The starting point was Fukutoshin Line platform on the B5 floor. For the map-reading part of the investigation, the participants were

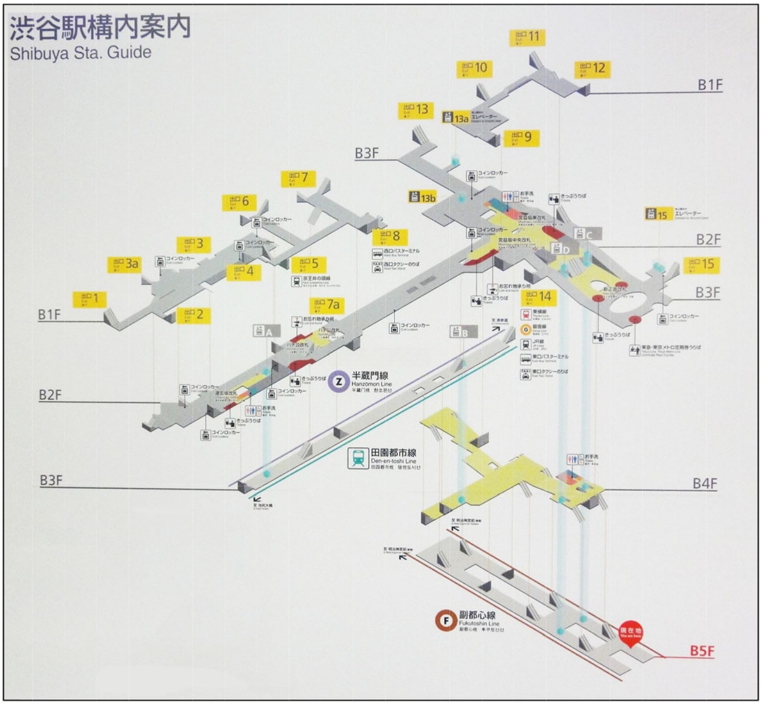

Fig. 1 Mounted maps of Shibuya station (Copyright © East Japan Railway Company. Photo by the author at Shibuya station)

required to complete four tasks: (1) a YAH task, in which they determined their own location; (2) a direction judgment task, in which they pointed out the direction of the destination; (3) a

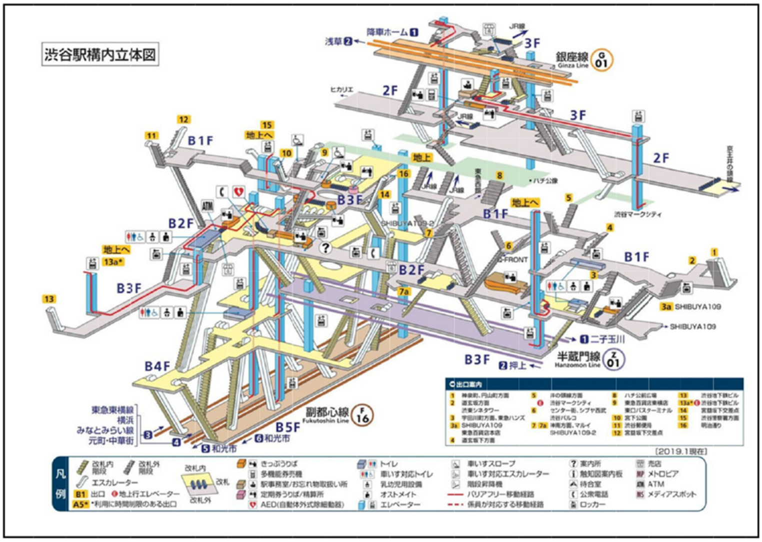

Fig. 2 Hand-held paper map of Shibuya station. (Copyright © Tokyo Metro Co., Download from https://www.tokyometro.jp/station/shibuya/yardmap/index.html#adjacent)

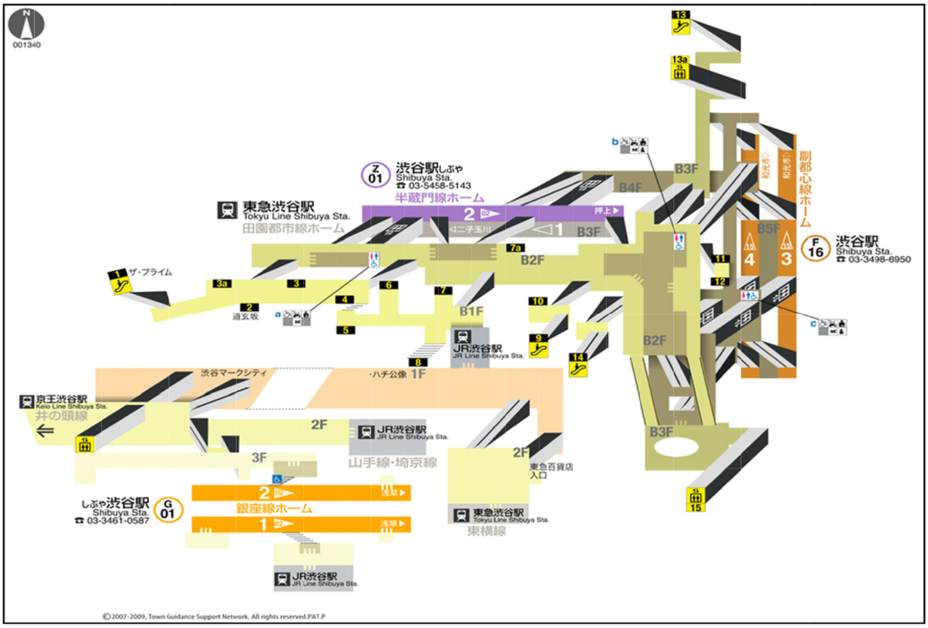

Fig. 3 Digital map of Shibuya station (Download form iOS app store. http://ekipedia.jp/services/iphone3.html)

route planning task, in which they planned a route from the starting point to the destination; and (4) a distance estimation task, in which they estimated the distance of the planned route.

The proposed model is based on the three main components of a route description previously identified by Michon and Denis [28]: action, landmark, and spatial entities. An action represents the displacement behaviour of a human acting in the environment. A landmark is the most salient feature used in human navigation. Spatial entities denote two-dimensional entities on which moves are executed (e.g., a street) or non-salient and non-punctual entities used in navigation (e.g., a forest). The approach is first experimented in the context of a natural environment. In order to do route description analysis, David Brosset et al. [33], based on this theory, develops a model for route description, turning the description into a symbolized procedure. He employs various symbols to replace those actions, landmarks, and spatial entities in description. This transformation is very helpful in the analysis and data-compiling of route description.

Following completion of the map-reading part, participants moved to the wayfinding task in which they had to walk to their destination. After they had done so, they were asked to evaluate three types of map of Shibuya Station. The content of the survey questionnaire was divided into two parts: (1) evaluating Shibuya Station, in which items were adapted from the six items of underground space evaluation by Durmisevic [34]; and (2) evaluating the three types of map, which featured five evaluation items (Impression, Practicality, Design, Precision, and Comprehension). Finally, the researchers interviewed the participants regarding their thoughts about the process according to their wayfinding experience during the investigation. Camera glasses were used to record participants' behavior and think-aloud protocols throughout the whole process.

The think aloud method involves the analysis of recorded verbal (and action) protocols that result from asking subjects to voice their thoughts when executing particular problem-solving tasks. The thinking aloud is recorded by means of audio and / or video techniques, and these recordings may be used to derive protocols. Think aloud method leads to valid, and the most complete, data on cognitive processes [35]. In many cases, the think aloud method is a unique source of direct and in-depth qualitative information on cognitive processes [36].

Downs' wayfinding model demonstrated that people receive information, evaluate it, transform it into images, and finally make a behavioral decision. This study used Downs' wayfinding model as its foundation and conducted coding for words and terms that the experimental process required. Concurrently, suitable new coding were added according to the research purpose. To ensure the accuracy of coding, two experts were asked to perform coding on the researchers' words and terms. Cohen's kappa coefficient was required to be generally greater than 0.7, which ensures coding reliability [35] and verbatim coding credibility.

Three main standards of coding (Table 1):

1. Perceptual Receptors: Information inputs: When wayfinders walk, they read maps and signs and simultaneously pay attention to facilities such as front gates and toilets within a field, and spatial characteristics. These objects serve as the foundation for receiving spatial information.
2. Value system: order parameters: In this stage, wayfinders start to evaluate their spatial information and match it with their actual environment. If the match is successful, images are exported from within, whereas if the match is unsuccessful, a conflict occurs. For example, participants may consider a map to be incongruent with their actual environment after reading it.
3. Decision: output: The final stage concerns making an action decision. The optimal scenario is if wayfinders can decide their direction and displacement strategy and successfully walk their planned route. If problems occur, the wayfinders can seek assistance. The worst-case scenario is if wayfinders become lost because they are unable to make decisions and find landmarks.

4 Results

4.1 You-are-Here task

The mounted maps featured YAH symbols, and therefore, the group using them did not need to find their location. By contrast, the paper maps and digital maps did not have YAH symbols; therefore, the groups using them were required to indicate their location on the maps. Nine

Table 1 Criteria for coding wayfinding verbalization

Perceptual receptors(P) External inputs	Value system (V) Order parameters	Decision (D) Outputs
*Map (PM) *Sign (PS) *Facilities (PF) *spatial characteristics (PSC) *others (PO)	*Internal output (VI) *Conflicts between internal image and actual environment (VCI) *Conflicts between map and actual environment (VCM)	*Action (DA) *Search (DS) *Lost (DL)

digital-map users and five paper map users correctly indicated their location. The digital-map users' mean distance error (distance between the location they indicated and their actual location) was far lower than that of the paper map users ($p < 0.05$) (Table 2). Furthermore, the time that digital-map users required was less than half that of the paper map users ($p < 0.04$). These initial results suggest that the digital map was more effective in conveying YAH, compared with the paper map.

However, how did the participants determine their location in the underground station? Why was the performance of the digital-map users superior to that of the paper map users? Was the difference in performance related to information provided on the map? According to the decision model of Passini [1], users use the corresponding relationship between their expected image and perceived image to make decisions. Landmarks on the map were the users' expected image whereas landmarks in the actual environment were the users' perceived images. Positioning and searching is hierarchical and gradually decreases from a broad scope to a small scope. The researchers discussed landmarks that successfully corresponded to users' expected and perceived images.

To understand users' orientation process, the researchers analyzed participants' speech through the camera glasses, which showed that two types of map users mentioned landmarks on the map and landmarks in the actual environment. Targets in the actual environment included landmarks (e.g., Fukutoshin Line, platform no. 3, Wako city, and signs on the B5 floor), facilities (escalators and trains), and spatial characteristics (edges and skylights). The accumulated frequencies of landmarks are illustrated in the Fig. 4. The investigation results indicated that both paper and digital-map users knew that the starting point was the platform of the Fukutoshin Line and they saw the signage for the Fukutoshin Line on the map (Fig. 4). However, they failed to realize where they were on this line. A total of seven digital-map users successfully used platform 3 as a cue for orientation, but no paper map users did the same. This was because even if the three paper map users attempted to use platform 3 as a cue, they could not find the signage for it on the map. Their failure to verify platform 3 rendered the cue useless. The cues that the paper map users used the most was the "To Wako City" sign on the map. However, Shibuya Station is the terminal station of the Fukutoshin Line, trains on platforms 3 and 4 travel in the same direction, and the users did not know what platform they were on.

Based on the actual environment, using the signage for platform 3 was obviously more useful for orientation than using the "To Wako city" signage because there was only one platform 3. Moreover, the signage for platform 3 on the digital map was larger and more visible than that on the paper maps. Directly marking them on the color blocks of the platform made them correspond more effectively with the actual platform, which enabled simpler and intuitive understanding. In addition, six digital-map users successfully used the cue of the edge of the terminal station platform. Landmarks on the edges of the 2.5D digital maps were clearer than those on the paper maps.

Table 2 The results of You-Are-Here task

Map	Paper map		Digital map		Total
	Mean	Std. D	Mean	Std. D	Mean
Time (sec)*	113.8	88.53	46.7	27.54	80.25
Error of distance (m)*	34.86	43.13	8.134	25.72	21.49

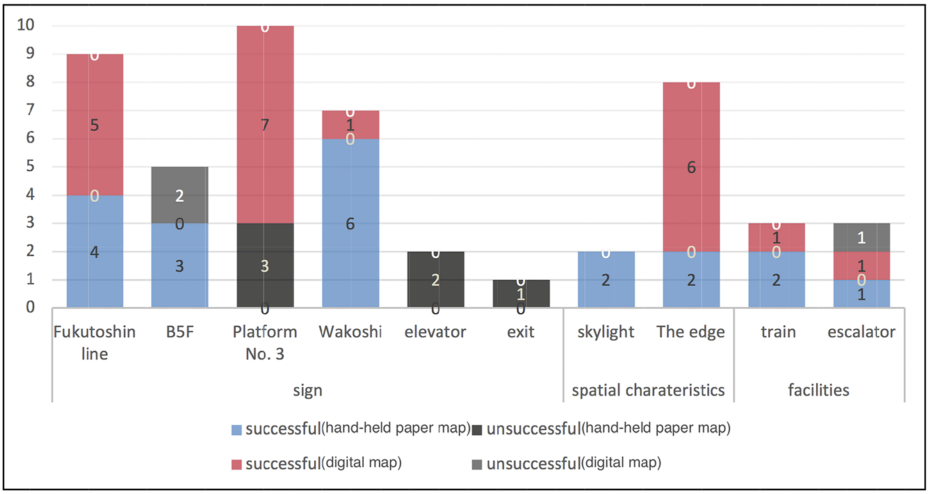

Fig. 4 The landmarks-checking of hand-held paper map users and digital-map users

4.2 Judgment of direction task

The absolute accuracy score (AAS) represents the average percentage difference between the objective direction values (ODV) and the cognitive direction values (CDE) [37].

$$\mathrm{AAS} = \left[\sum_{i=1}^{n}\left(\frac{ODV-CDE}{180}\right)\times 100\right]\div n.$$

The average AAS values of the three types of map users were 17.6° for digital-map users, 40.4° for mounted-map users, and 73.6° for paper map users. Map type was significantly correlated with directional errors ($p = 0.036 < 0.05$).

The following figure presents the AAS values of all 30 participants (Fig. 5). Evidently, the standard deviation in AAS values between digital-map users was relatively small and that between paper maps users was relatively large. That is, digital-map users could judge the direction of the destination more effectively than could paper map and mounted-map users.

The mounted maps and paper maps featured view angles and might be incomplete in users' cognitive maps. Perspective drawings usually cause a distortion in the angle of an image; for example, a 90° crossroad may be converted into a 120° one. Consequently, mounted-map and paper map users must consider such angle distortions to understand what they are looking at. By contrast, the digital map was drawn from a top-down perspective and the visual angle was the same as the actual environment, which facilitated participants judging the direction of the destination.

4.3 Route planning task

4.3.1 Results of planning route task

The results indicated that map type did not influence the time required to plan routes (Table 3). However, individual time differences in digital-map users were smaller than those in paper map and mounted-map users.

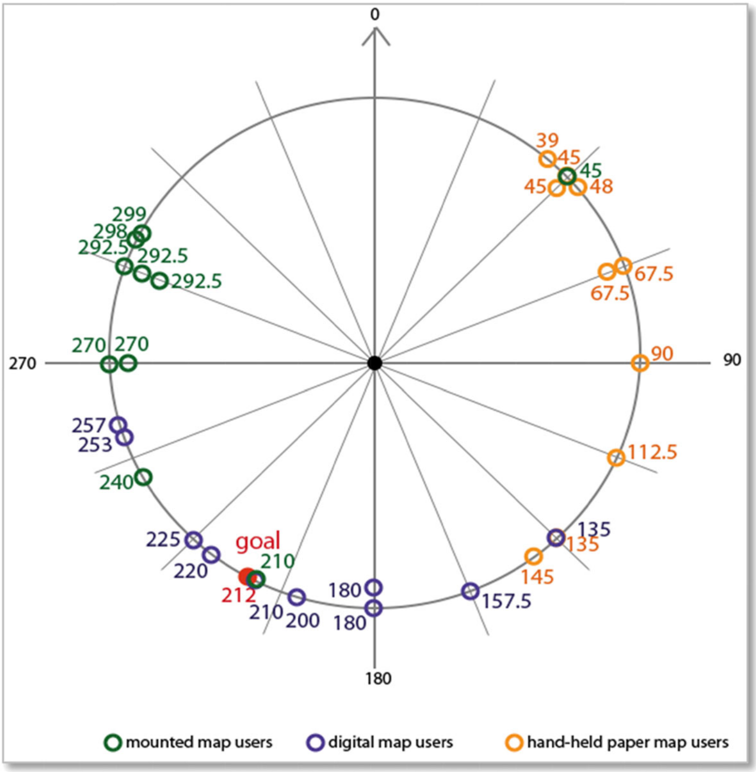

Fig. 5 Three map users' estimations of goal directional

4.3.2 Verbalization of planning routes

The numbers of landmarks and times participants stopped were strongly correlated ($p = 0.039 < 0.05$). Those who used more landmarks found their way more smoothly and had almost no stops. Table 4 analyzes the information these participants used when planning their routes. The

Table 3 Results of route planning route task

Map	Mean/N/Std.D	Distance (m)	Time (sec)	PAO
Mounted	Mean	229.9100	176.50	1.1639
	N	10	10	10
	Std. Deviation	37.77743	90.467	.19123
Paper	Mean	231.5700	162.40	1.1723
	N	10	10	10
	Std. Deviation	34.35469	100.062	.17395
Digital	Mean	247.1800	134.00	1.2513
	N	10	10	10
	Std. Deviation	30.15268	41.593	.15257
Total	Mean	236.2200	157.63	1.1958
	N	30	30	30
	Std. Deviation	33.96990	80.668	.17195

Table 4 The frequency of actions and landmarks

Map	Action	Landmarks*		
		Specific landmarks**	Non-specific landmarks	Total
Mounted map	119	37	24	61
Paper map	109	24	28	52
Digital map	120	55	26	81

researchers recorded the frequency of participants' actions and the number of landmarks they used along their planned routes by listening to their speech through the camera glasses.

Regarding the planned routes, the frequency of landmark use differed significantly among the three groups ($p = 0.028 < 0.05$). Digital-map users had the highest frequency of landmark use, whereas paper map users had the lowest frequency. Although the paper maps featured the most landmarks among the three map types, the results indicated that paper map users were unable to use the maps effectively. These users mentioned that they could not comprehend the meaning of the landmark symbols, and some even showed an unwillingness to read the landmarks on the map because of how difficult they were to comprehend.

For example, various 3D views of landmarks were shown on the paper maps.

However, in the map key that explained the landmark symbols, some had similar designs, making them difficult to comprehend. Some participants stated that they could not understand the meaning of the icons (Fig. 6). This indicated that similar designs for landmarks should be avoided and explanations should be provided in several languages.

Map type was significantly correlated with the use of specific landmarks ($p = 0.005 < 0.01$), which were usually names or codes. Specific landmarks in the station included exits, floors, lines, train directions, and platforms. These were marked on the three maps; however, their different layouts resulted in different usage rates. Specific landmarks should have the highest importance. As the YAH task demonstrated, the identification of specific landmarks was more effective than that of nonspecific landmarks.

Digital-map users had the highest frequency of using specific landmarks, which on digital maps were clearer and considerably larger than those on mounted and paper maps.

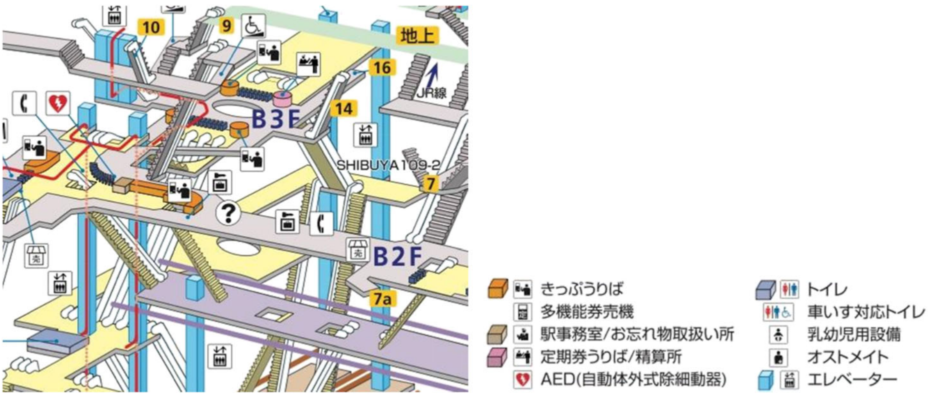

Fig. 6 Various 3D views and symbols of landmarks (Copyright © Tokyo Metro Co., Download from https://www.tokyometro.jp/station/shibuya/yardmap/index.html#adjacent)

Normally, a map features numerous icons, which help readers to recognize and understand the map. Different types of landmark are exhibited differently according to their importance. The most crucial sign should have the strongest visibility. Visibility and hierarchy can often be presented using different design techniques, such as size, color, images, and lines of varying thicknesses. A stratified presentation can accelerate readers' comprehension and information acquisition.

4.3.3 Incorrect and confusion in planning route

Map type and frequency that participants expressed confusion were strongly correlated ($p = 0.036 < 0.05$). When mounted-map users planned their route, their confusion was twice that of hand-help map and digital-map users (Fig. 7). This indicated that mounted maps were the most difficult to comprehend.

Notably, mistakes made by participants were mainly related to the ticket gates and stairs. Users of the three types of map ignored the restriction of the gates on their movement. This was particularly true for digital-map users because 9 participants ignored this restriction. Different colors were used to indicate the areas restricted and not restricted by the ticket gates on the maps and specific explanations of the signages for the ticket gates were provided on the paper map. However, these efforts were insufficient for attracting the participants' attention. The digital-map users mentioned that they could not comprehend the meaning of the ticket gate signages. Therefore, to enable a smoother wayfinding experience in the station, a reminder to wayfinders on the map regarding the restriction posed by ticket gates is necessary. Specifically, the visibility of the images and the division of areas restricted by the ticket gates should be enhanced.

Mounted-map and paper map users often misjudged the location of stairs and expressed confusion several times. This indicated that how stairs were presented on these two maps was misleading. Mounted-map users mentioned encountering difficulties in understanding the map

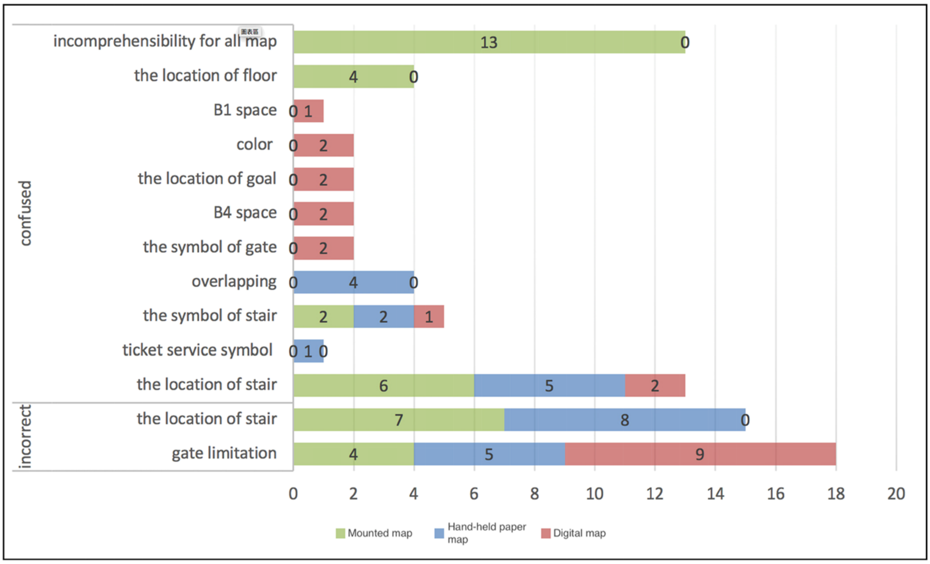

Fig. 7 The part of conflict report

several times. The mounted map was the largest of the three, and thus, it should be able to present information clearly. However, to avoid the overlapping of floors, the mounted map was presented using an exploded view. However, the signboard users were highly confused about the thin line leading to the stairs, and they were unsure of the relationship between floors. Even though the paper maps had the most information and most detailed content, the overlapping of floors made the location of stairs unclear, which caused users to lose their direction.

4.3.4 Distance estimation task

Although the estimated distance between all groups did not differ significantly, it was longer than the actual distance (Fig. 8). This result revealed that the maps did not feature a map scale, causing the participants difficulty in determining the time required to move from one point to the next.

4.4 Wayfinding task

The results indicated that map type did not have a significant relationship with wayfinding. However, map type did affect the amount of time required to read the map when participants were walking ($p = 0.003 < 0.01$). Digital-map users spent the most time reading the map but the shortest time stopping (Table 5). This showed that digital-map users tended to read the map while walking. Mounted-map users had the shortest reading time even they had to stop to read the map. Another notable finding was a strong relationship between walking time and AAS value ($p = 0.005 < 0.01$, $r = 0.5$); furthermore, a strong relationship also existed between stopping time and AAS value ($p = 0.027 < 0.01$, $r = 0.56$). Users with smaller deviations were estimated to have shorter walking and stopping times. This suggested that users with superior comprehension of spatial relationships and greater knowledge acquisition had a smoother wayfinding ability.

The verbalization in wayfinding of users of the three kinds of maps are analyzed in Fig. 9.

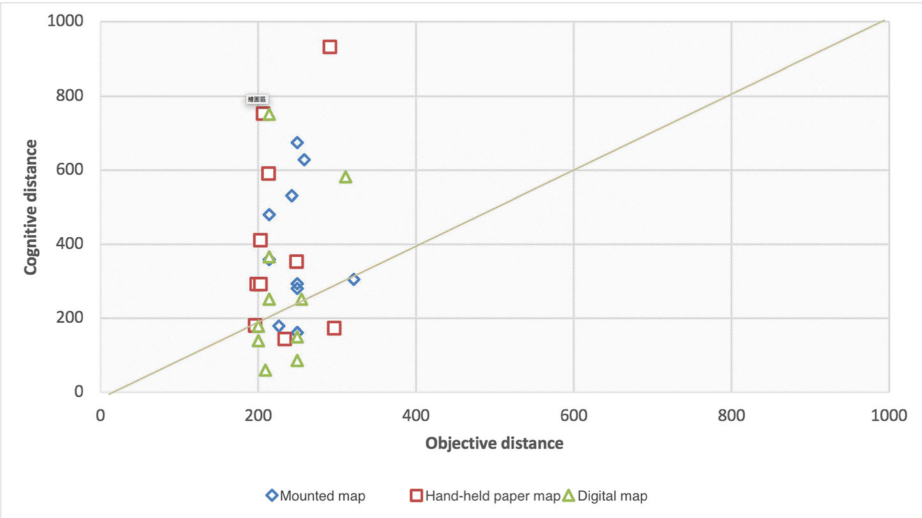

Fig. 8 Map users' distance estimation

Table 5 Results of wayfinding

Map	Mean/ SD	Wayfinding distance (m)	Wayfinding (sec)	W/P	Total time (sec)	Stop (n)	Stop time (sec)	Read time (sec)	R/ W
Mounted	Mean	295.14	660.00	1.30	836.50	7.50	136.20	84.40	.108
	SD	69.51	222.933	.35	234.98	3.68	135.17	113.11	.109
Paper	Mean	299.64	803.20	1.28	965.60	9.10	254.20	192.50	.226
	SD	73.32	270.700	.18	277.21	3.84	150.26	134.90	.101
Digital	Mean	296.99	593.40	1.21	727.40	5.60	67.70	260.40	.443
	SD	31.42	125.358	.15	120.98	3.74	47.025	145.61	.229
Total	Mean	297.25	685.53	1.26	843.17	7.40	152.70	179.10	.259
	SD	58.97	225.762	.24	235.23	3.90	139.65	147.08	.207

W/P=Wayfinding distance/Planning route distance

Total time = route planning time + wayfinding time

R/W = reading map time/wayfinding time

1) perceptual receptors

Mounted map users pay less attention to sign information (PS) than other users do. Digital map users have more map verbalization (PM) than other users do.

2) value system

Paper map users have more Vis than other users do. Digital map users have fewer (VI) and (VCI) than other users do. They seldom contrast the map in their minds with real surroundings and have much more (PM) verbalizing. They spend so much time reading while walking. These all show that digital map users tend to directly contract the map with surroundings. The portability of the map and its 2.5D plan view together has resulted in this new wayfinding model.

3) decision

Mounted map users have more goal-searching verbalizations (DS) than other users do, and the goal here is mostly the map itself. This shows the problem that users cannot get the information they need when they have to read it. On the contrary, digital map users

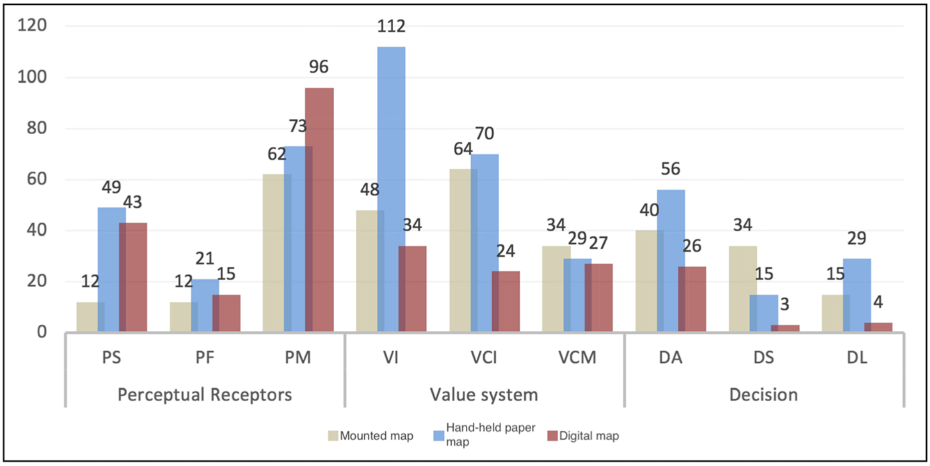

Fig. 9 Verbalization in wayfinding. *Map (PM), Sign (PS), Facilities (PF), spatial characteristics (PSC), others (PO); Internal output (VI), Conflicts between internal image and actual environment (VCI), Conflicts between map and actual environment (VCM); Action (DA), Search (DS), Lost (DL)

have much fewer goal-searching verbalizations. Although paper map users take the map with them, they have the most number of (DL) verbalizations. Many paper map users showed that they were not able to orientate and lose their way. Some even did not use the map anymore and only follow the directional sign of the exit.

4.5 Questionnaire

Once all 30 participants had completed all their tasks, they were asked to fill out two questionnaires: one evaluated Shibuya Station and the other evaluated the three types of maps. The results revealed that participants provided positive feedback for five out of the eight criteria and negative feedback for the remaining three in the first questionnaire. The three negative factors were shelter, visibility, and orientation, which were most strongly linked to wayfinding activity. Regarding the three types of maps, participants all evaluated paper maps positively and digital maps negatively. Mounted maps also received largely positive evaluations, but not for factor of impression. Paper map users thought that mounted maps had high usability, which could be because of the absence of YAH symbols in paper maps. Moreover, paper map users considered their map to have relatively low usability, but mounted-map and digital-map users considered their own maps to have high usability. Different from the other two groups, digital-map users considered paper maps to have high precision but considered mounted maps to be difficult to comprehend.

Evaluations of the station indicated that adding several aspects of wayfinding support is necessary to move effectively and freely in its underground spaces.

Evaluation of the maps showed that differences between groups were comprehensive. For example, paper map users considered mounted maps to have the highest usability, but mounted-map and digital-map users considered paper maps to have the highest usability. They all considered digital maps to be the worst (Fig. 10). However, the results of the task showed that digital-map users had the fewest errors, including YAH judgment and direction,

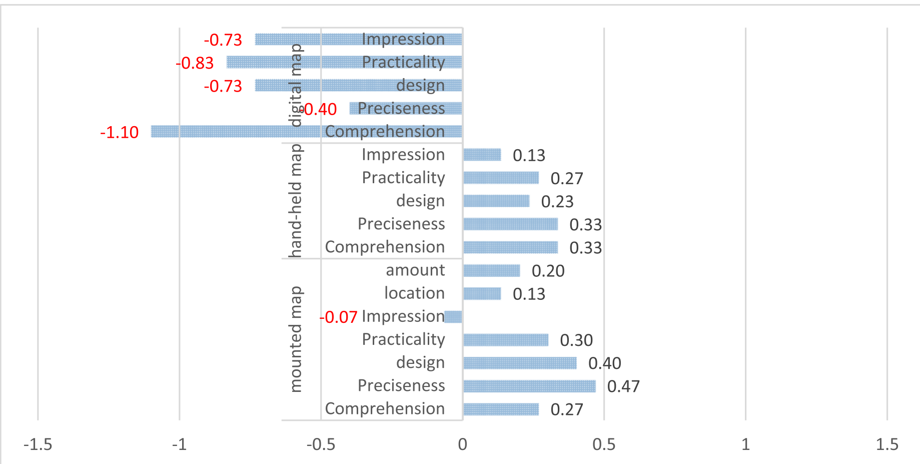

Fig. 10 Evaluation of map design

and they also spent the shortest time on wayfinding on average. This indicated that users were unable to estimate the necessary information when actually walking by merely reading maps.

Although digital-map users provided less negative feedback, they were still unsatisfied with their map. A total of 17 participants selected mounted maps as their next wayfinding tool. This showed that participants preferred the large scale of the mounted map, which was because they did not need to prepare maps in advance or locate themselves again.

5 Discussion

Successfully matching the maps with the actual environment can enable successful wayfinding and create useful spatial knowledge.

Participants in the YAH task could effectively ensure their own direction using specific landmarks, such as train routes, station platforms, floors, and exits. Compared with paper map users, digital-map users had more precise and rapid judgment of exactly where they were. This was because platforms signs on digital maps could be read accurately, whereas those on paper maps were relatively difficult to find and understand. Therefore, the visibility of specific landmarks on the maps such as platforms should be enhanced. Moreover, adding the number of specific landmarks, including public art, special spatial patterns, and facility codes can help users reorient themselves in the correct direction in a timely manner. Exclusive landmarks should be chosen and marked on maps, and landmarks should use be identifiable with numbers, code, names, or in the form of public art.

In the direction judgment task, the standard deviations of AAS values of digital-map users were smaller than those of other users. The paper and mounted maps were made using perspective drawings, which featured distortion in angles and were susceptible to being misinterpreted. The digital maps were made using 2.5D drawings, which retained the advantages of a floor plan, facilitating directional judgment.

In the route planning task, participants who used more landmarks stopped less and had smoother wayfinding processes. Even though paper maps had the highest number of landmarks, these landmarks were the least used by participants. This was because their signage lacked a stratified presentation according to their importance (see the following figure). In addition, their designs were not clearly distinguishable. In terms of route planning, the problems participants encountered most occurred at stairs and ticket gates. For example, some stairs could not be completely shown on perspective maps (see the following figure). Participants who used mounted maps found it difficult to comprehend the lines connecting to the stairs. Stairs on paper maps overlapped with elements of other images. Passengers must pass through ticket gates to reach outside areas, which is a crucial node point during the wayfinding process. However, the results revealed that participants easily ignored the restrictions posed by the ticket gates. Therefore, the visibility ticket gates on maps must be enhanced to distinguish between different areas (Fig. 11).

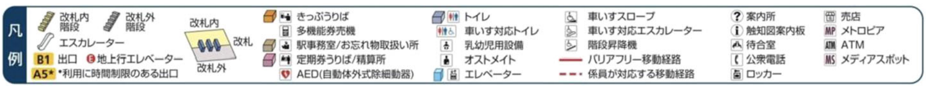

Fig. 11 Stratified presentation of landmark icons (Copyright © Tokyo Metro Co., Download from https://www.tokyometro.jp/station/shibuya/yardmap/index.html#adjacent)

In the wayfinding task, digital-map users spent the most time reading the map, and according to their speech, they acquired the most information from the map. However, they spent less time speaking when wayfinding, which showed that they tended to match the information they acquired from the map with the surrounding environment immediately when walking. The mobility of digital maps supports this new wayfinding model.

Participants who used paper maps lost their way most frequently; several mentioned that they were unsure where they were when they checked the map again. Eventually, they walked in the direction of the exit closest to the target without reading the map and failed to locate themselves.

Mounted maps were mounted on the walls and had YAH symbols. Participants were unable to read the map immediately when they encountered difficulty and required more information. They detoured to read other mounted maps and paid the least attention to direction signs.

Overall, digital-map users had higher precision in terms of locating themselves than paper map users. This was mainly because digital-map users successfully matched platforms in the physical environment with platforms on the map. Conversely, paper map users did not examine or recognize platform symbols on the map. When asked to indicate the destination on the map, digital-map users demonstrated a clearly stronger sense of direction than did other map users. Additionally, mounted-map users clearly expressed greater confusion than did other users when reading mounted maps.

Users of the three map types easily ignored the restriction posed by ticket gates. This was particularly true for digital-map users, nine of whom planned routes outside the area of the ticket gates and two of whom could not comprehend the symbol for the ticket gates. They could not plan a reasonable route by only reading maps. By contrast, the mounted-map and paper map users experienced considerable problems and confusion when attempting to locate the stairs. Mounted-map users expressed that they could not determine the location of stairs using the thin lines on their maps. Paper map users mentioned that they could not find stairs with the same symbol. Notably, some participants in all groups used distance as their cue for making a turn or ascending stairs. They estimated the distance, which was 20% longer than the actual distance.

No significant difference existed between the three maps in terms of wayfinding efficiency; however, significant differences existed in terms of application method. Mounted-map users detoured because they wanted to find other mounted maps and spoke the most about searching for the destination. Paper map users had to follow on-site directional signs because they could not locate themselves, and furthermore, they spoke most frequently about being lost and reading directional signs. Digital-map users spent more than 40% or their time reading while moving and spoke the most about information on the map. Compared with other map users, digital-map users spoke the least about searching for targets and being lost. (Table 6)

The task results enhanced the researchers' understanding of the problems encountered by participants when using maps. These problems stemmed from the differences between the perceived images of participants, the actual environment, and the maps. As previously mentioned, during map-reading, differences existed between the perceived image of readers and those of designers. The researchers found two additional differences after observing the on-site wayfinding: the first was a difference between the actual environment and the image of wayfinders, and the second was a difference between the actual environment and the maps.

1) Difference between perceived image of readers and image of designers

The investigation results showed that even for the same spatial information, map

Table 6 Results of three groups

Tasks	Mounted- map	Paper map	Digital map
You-Are-Here task		5 users out of 10	9 users out of 10
Judgment of direction	40.4 degree	73.6 degree	17.6 degree
Route planning task	Ignorance of the gate restriction (4 users)	Ignorance of the gate restriction (5 users)	Ignorance of the gate restriction (9 users)
	Mistakes of stairway location (7 users)	Mistakes of stairway location (8 users)	0 users
	21% specific landmarks	15% specific landmarks	27% specific landmarks
Distance estimation	80% longer	21% longer	60% longer
Wayfinding task	Detour 31%	Detour 28%	Detour 21%
	Stop time 136 s	Stop time 254 s	Stop time 68 s
	Reading map time 11%	Reading map time 23%	Reading map time 44%
	Lost report (4 users)	Lost report (8 users)	Lost report (3 users)
	The use of the sense of distance (2 users)	The use of the sense of distance (2users)	The use of the sense of distance (1user)
	Mounted map users detoured a lot in order to find one map.	Paper map users need to follow directional signs because of failing to orient themselves.	Digital map users reading map while walking.
Evaluation	Expect impression item, positive feedback	Positive feedback	Negative feedback

readers will have a different understanding of the spatial information if the spatial dimensions and visual variables differ. For map designers, examining the types of symbol that may confuse readers or adding necessary information is critical.

The researchers found during the investigation that users struggled to distinguish the location of staircases on the different floors. When one was marked separately on two floors, users could only match the two floors through guessing or examining lines in the image. Therefore, the connections between floors and the location of stairs were crucial. To make stairs visible, designers can use different colors or codes to enhance the difference between symbols. However, subway stations may have many staircases, and thus presenting them with different colors on the map could be highly difficult. Another method is to use specific numbers to code each staircase, which would help to ensure the location of the stairs.

In addition, the results indicated that digital-map users had superior direction judging ability than did other map users. Digital-map users could understand the spatial relationship between different floors. Designers can incorporate orientation labels on perspective images, which could prevent readers misunderstanding that each angle in the image is 90°.

In the YAH task, the platform symbols were not sufficiently large on the paper maps and readers did not notice this key cue, and thus, were unable to locate themselves. Therefore, specific landmarks are a crucial piece of information and should be sufficiently clear on a map. Ticket gates in subway stations are unique; for example, although Shibuya Station uses three different colors to indicate areas inside and outside ticket gates for the three types of map, this effort was in vain because these differences failed to attract the attention of users. Digital-map users even indicated that they could not understand the oversimplified gate symbol. This was particularly true for perspective images where designers did not draw separation barriers and readers more readily ignored this restriction. Therefore, enhancing the visibility of ticket gate symbols and even adding symbols for barriers could attract readers' attention. Furthermore, in the digital maps, the color of each floor was similar to that of other floors, and thus, users were unable to distinguish between colors of different floors, which resulted in the lack of a memorable stratified spatial structure. Therefore, a more apparent structure can help users to construct their perceived map image and reduce the time required to read the map.

Finally, maps usually feature a scale, but the maps in the present investigation did not have one. The results indicated that when making a turn, the wayfinders usually used distance as a reference, and their estimated distances were usually 20% longer than the actual one. Some users doubted whether thin passageways on the maps were accessible, which suggested that the provision of a map scale is necessary. They can help people to use distance as a cue, estimate the distance, and support their strategy.

2) Difference between the environment and images of the wayfinders

Regarding orientation, paper map users could not determine their own direction because the information they acquired from the maps was incompatible with the actual environment. Some participants returned to landmarks that they had examined previously to relocate themselves. A lack of specific landmarks and spatial characteristics in underground stations is a prevalent problem. Route description results showed that these users usually used stairs as their landmark but were unable to distinguish which stairs were the one they wished to find in the actual environment. By contrast, exits with numbers were specific landmarks and they were not confusing to participants. Therefore, stairs should be coded on maps and coding symbols placed at the location of stairs. This will enable map readers to see the actual coding on stairs, match them with the information on the map, and determine where they are. In this manner, stairs in an underground station can be used as reference and even as specific landmarks, enabling repeated successful matching.

Through investigating the maps, the researchers found that users were unable to obtain information from maps anytime and anywhere, and users' images of the maps weakened gradually in their wayfinding process. When they no longer remember the image, they detoured to find another map. Therefore, map information should be provided in places where decision-making problems occur, such as adjacent stairs, gates, and crossroads.

3) Difference between the actual environment and maps

This difference was actually caused by inconsistencies in the maps. The map designers ignored some factual information when making the maps. For example, digital-map users discovered two staircases on site, but only one was shown on the map. Such inconsistent images reduce the reliability of the maps and influence map users' decisions. To reduce inconsistency, map designers must devote their best efforts to providing complete information. For example, if one single staircase is marked on a map, all staircases should be marked by clear symbols. Stairs, escalators, and elevators are unique. Therefore, explanations should be provided for adjacent stairs and escalators. Another problem was that the 3D perspective view was incompatible with the actual environment. Consequently, users were unable to compare the route they saw at a complex intersection with the same one on the map. Therefore, perspective images with angles that matched closely with that of the actual environment can be selected when drawing and designing maps. Alternatively, the map-reading direction can be indicated by the YAH symbol. This will enable users to determine the direction they are facing and use it as a basis for comparing passageways in the actual environment and passageways on the map.

6 Conclusion

The view angle of 3D maps differs from that of the human eye. Therefore, errors may occur during the acquisition of information from an environment after reading maps. The wayfinding task revealed that most erroneous decisions arose from participants' overestimation of the environmental information they obtained. Although 3D maps can show a full view of spaces, the results showed that areas on 3D maps often overlap. Consequently, the participants were unable to recognize the spatial relationship between floors, and thus struggled with judging the location of stairs. Stairs were frequently used as landmarks, but they were not featured as specific landmarks on the maps. Participants struggled to differentiate between stairs and failed to do so in their wayfinding process. Coding stairs on maps can help map readers to correctly locate them. Furthermore, in the actual environment, signage should be created for stairs, transforming them into specific landmarks.

Exits were one of most frequently used landmarks. However, the distance between platforms in the underground station as well as its exits were extremely long. Additionally, almost no obvious landmarks existed between platforms and entrances and exits during the wayfinding process; hence, no wayfinders knew where they were. Similarly, participants easily ignored the restriction posed by ticket gates when using paper maps to plan routes. They often felt confused when they encountered ticket gates during the actual wayfinding process.

Therefore, regarding stairs, exits, and ticket gates in the underground station, designing stronger, clearer signs on maps is necessary. Specifically, this includes enhancing the visibility of ticket gate signage and providing further explanations of areas inside and outside the ticket gates. By coding ticket gates on the map as specific landmarks and adding spatial features such as signages to the actual environment, the number of effective landmarks can be increased; these are extremely helpful for people to locate themselves and recognize routes.

Edges on maps are usually considered a type of landmark or spatial characteristic for orientation. Therefore, if maps can clearly show these spatial characteristics, misunderstandings can be effectively avoided. Moreover, the results showed that users were required to zoom between the map and the actual environment. Some participants used distance as a cue that indicated where they should make a turn, and thus, the ability to estimate distance is crucial in wayfinding. Having a compass on the map will help show precise directions and remind readers to pay attention to distortion in angles. The view of map readers should match the map drawing direction. Furthermore, more maps should be placed at the crossroads near the ticket gates as well as at the stairs.

The ideal digital map is one with a global positioning system (GPS) equipped; however, GPS technology that can be applied to basements and other underground spaces is not mature. Alternately, 3D interactive maps can be used to provide users with enhanced information. Current functions provided by digital maps include starting points, destinations, and route planning. Because of size limitations, the most considerable disadvantage of digital maps is difficulty with panoramic views. Users can only view part of a map on their mobile device. Therefore, problems such as the timing of zoom-in/out when reading digital maps must be reconsidered.

The use of paper maps is more time-consuming in terms of understanding the corresponding relationships between symbols, signs, and current environments than digital maps. Most importantly, what is needed is a wayfinding program that systematically integrates multiple wayfinding elements into a consistently applied design program. Playback and analysis of participant videos did allow us to identify specific information that was missing, including critical landmarks and the locations of common route errors. Following this effort, we plan to revise the map accordingly and conduct additional user testing evidence-based design.

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