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Number of Participants in the Application of Evaluation Methods for Digital Maps Accessed by Mobile Devices

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Determining the ideal number of participants to involve in usability tests of digital maps on mobile devices is challenging due to the specific context of mobile map use, including dynamic environments (indoor versus outdoor), interaction while in motion, small screens, and environmental distractions. This meta-analysis encompasses articles published between 2010 and 2024, comparing evaluation methods (field testing, laboratory testing, and eye tracking), testing conditions, and the number of participants employed. The results indicate a predominance of small sample sizes, reflecting the widespread adoption of compact usability studies, although adaptations are often required to address the specific demands of mobile contexts. We identify mobile-specific factors that may require hybrid approaches or larger sample sizes in certain scenarios, providing practical implications for sample size planning and the development of new methodologies for evaluating interactive digital maps.

KEYWORDS: mobile maps; usability testing; systematic review; smartphones; sample size.

INTRODUCTION

It is common for researchers to take usability evaluation techniques from the study of human-computer interaction and apply them to the study of map usage. However, these techniques do not cover all necessary aspects of the design of user testing procedures for maps. While many studies prioritize the identification of problems with interface design (Fogli et al. 2020, Bartling et al. 2021), researching map use usually requires examining a broader set of aspects than just the interface, such as users' spatial perceptions, navigation behaviors, attitudes, and route choices (Chu et al. 2017, Matsuo et al. 2020, Vincent et al. 2022, Prandi et al. 2023).

In cartographic representations accessed via mobile devices, usability evaluations must consider factors such as interaction while in motion, small screens, and dynamic usage contexts. Although some of these factors may also occur with static maps, they are more prevalent in mobile map use and introduce challenges that necessitate approaches specifically tailored to testing mobile maps (Çöltekin et al. 2017, Schirmer et al. 2015, Swobodzinski et al. 2021). For example, tasks requiring users to identify points of interest (POIs) on a map are often best supported by qualitative methods, such as the think-aloud protocol (Rehrl et al. 2012, Fogli et al. 2020, Nair et al. 2022). Conversely, quantitative tasks that assess temporal efficiency and error rates are generally better suited to larger samples and are frequently complemented by questionnaires (Martins et al. 2023). Although these methodological approaches are not exclusive to mobile map research, their selection in mobile map usability studies is also influenced by whether the evaluation is conducted in a controlled environment, such as a laboratory, or in an uncontrolled environment, such as a field setting (Liang et al. 2012, Kratz et al. 2010, Einfeldt and Degbelo 2021).

Amidst the complexities of measuring map use, it can be particularly challenging to determine the ideal sample size (Eraslan et al. 2016, Shah et al. 2024). Because of this, while a multitude of map use studies have been conducted, the number of participants in these studies varies considerably. Many researchers have been influenced by the premise proposed by Nielsen in 1993, who asserts that five users can typically detect approximately 80–85% of usability problems. However, this rule, based on simple and static contexts, has limitations in complex and dynamic scenarios such as mobile maps, where contextual and cognitive factors demand larger samples or hybrid methodologies for greater robustness (see Schmettow 2012 for discussions in recent literature on mobile usability). Recent studies, including that of Martins et al. (2023), have examined sample sizes in studies of digital maps, yet these studies have not distinguished between mobile and static map contexts. Evaluations of digital maps exhibit considerable variations in their methodology and focus, varying in their emphasis on spatial behaviors, the utilization of diverse devices, dynamic environments, and the emotional fluctuations of participants (Montuwy et al. 2019, Dong et al. 2021).

Consequently, professionals in the field are frequently uncertain about the ideal sample size for mobile maps, when considering the variables of methodology, test conditions, and unique aspects such as indoor/outdoor environments and tasks performed in motion. In light of this, the present study offers a qualitative and quantitative meta-analysis of cartography publications, and an examination of methodological patterns in evaluations of mobile digital maps. We will compare test types, configurations, conditions (including indoor/outdoor environments), and number of participants. The objective of this study is to identify implications for sample size determination and to suggest methodological adaptations that can advance mobile cartography.

PROCEDURE FOR ANALYZING THE METHODS

The present study is based upon a systematic review and meta-analysis approach of articles published in international journals between 2010 and 2024. We consulted the Scopus and Web of Science databases, using the combined keywords *"usability" AND "maps" AND "navigation" AND ("mobile" OR "smartphone" OR "mobile devices")*. Our focus is on navigation and map use on smartphones, and so these search terms were intended to prioritize studies of maps accessed by smartphones, particularly those that focused on navigation tasks (i.e., the main functionality evaluated) and examined usability as a central dimension.

In selecting from the search results, we established the following inclusion criteria:

- The articles must be in English.
- The articles must report empirical studies of users evaluating mobile digital maps.
- Any studies of non-mobile maps are excluded.
- Purely thematic maps without interaction are excluded.
- Maps that are unrelated to usability or navigation are excluded.

Each article was subjected to a comprehensive analysis, encompassing the title, abstract, introduction, and methodology, to ascertain its relevance and the presence of the desired data.

We then subjected the selected articles to qualitative and quantitative analysis, examining each article's testing methods (e.g., eye-tracking, field/lab tests, questionnaires, think-aloud protocol), settings (moderated/unmoderated), the usability criteria evaluated, data type (qualitative/quantitative), environment (indoor, outdoor, or hybrid), application conditions (controlled/lab vs. uncontrolled/field), and number of participants. The participants were classified as either "specific" (with defined characteristics, e.g., experts) or "diverse/general" (broad audience without filter). The data were then meticulously tabulated for the purpose of conducting a thorough statistical comparison, encompassing means, distributions by method and environment, and critical analysis of patterns and limitations.

ORGANIZATION AND ANALYSIS OF RESULTS

The methods for evaluating mobile digital maps were categorized into four main groups, adapted from Rohrer's (2022) framework for user experience research. As illustrated in Figure 1, the grid consists of two primary axes.

- **Horizontal axis:** Attitudinal ("what people say" — self-reported beliefs, opinions, and perceptions) versus Behavioral ("what people do" — observable actions and actual interactions with the map).

- **Vertical axis:** Qualitative (direct data from observation or reports, answering "how" or "why") versus Quantitative (data measurable via instruments, answering "how much" or "how many").

The four resulting quadrants are:

- **Attitudinal-Qualitative (A):** Direct expressions of beliefs and reasons (e.g., interviews, focus groups, think-aloud protocols).

- **Attitudinal-Quantitative (D):** Numerical measurement of attitudes (e.g., surveys with scales, structured questionnaires).

- **Behavioral-Qualitative (B):** Direct observation of actions (e.g., observation of the user in the field/lab, qualitative eye-tracking).

- **Behavioral-Quantitative (C)**: Measurement of behaviors (e.g., task time, error rate, A/B testing).

The selected studies were classified into these quadrants based on their described methodology. Other

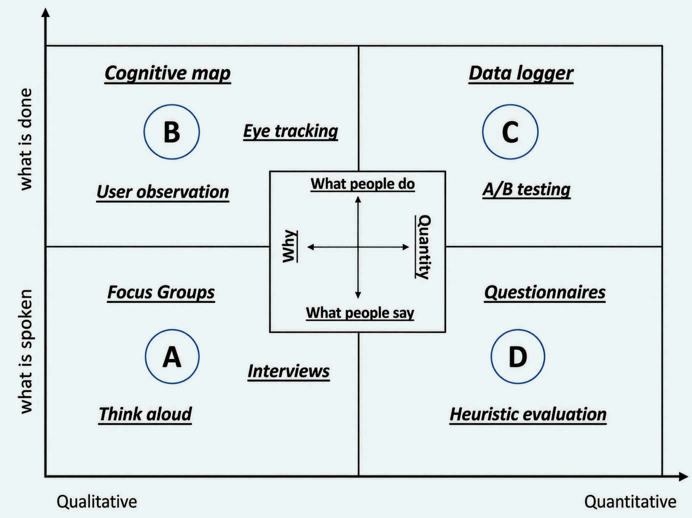

Figure 1. Framework of research methods in usability and user experience. Adapted from Rohrer (2022).

methodological data that we extracted from the source documents (method types, internal/external environment, target audience, number of participants, etc.) were tabulated and analyzed using RStudio software. The analyses encompassed the following:

- **Descriptive statistics:** Calculations of absolute and relative frequencies by quadrant/method.

- **Graphic representations:** Bar charts for categorical distributions; boxplots to compare the number of participants across quadrants, methods, and conditions (highlighting median, interquartile range, and outliers); and heatmaps (colored block charts) to visualize patterns in the cross-variable matrix (e.g., number of participants per quadrant and environment).

CRITICAL ANALYSIS OF METHODS FOR EVALUATING MOVING MAPS

We searched both the Scopus and Web of Science databases using the keyword combinations mentioned above. This yielded 115 articles from Scopus and 80 from Web of Science, for an initial total of 195, all published between 2010 and 2024. Following a thorough screening process involving the analysis of titles, abstracts, and methodologies, 53 articles were selected for further consideration. These articles reported empirical evaluations of human participants, focusing on digital maps accessed by smartphones. The empirical evaluations examined cartographic navigation and usability tasks in both real and simulated contexts. Theoretical studies, studies lacking participants, and studies devoid of a clear cartographic component were excluded from the analysis.

Table 1 presents a summary of the data collection methods employed in the 53 studies that were analyzed.

Article(s)	Method(s)	Correspondence with the framework (Figure 1)
Noguera et al. 2012 Brade et al. 2017 Sakpere et al. 2017 Lu et al. 2021	Questionnaire	Attitudinal-Quantitative (D)
Dirin et al. 2018	Interview	Attitudinal-Qualitative (A)
Link et al. 2013 Yang et al. 2019	Data logger	Behavioral-Quantitative (C)
Darvishy et al. 2020	Observation	Behavioral-Qualitative (B)
Maly et al. 2013 Montuwy et al. 2019	Interview and Data logger	Attitudinal-Qualitative (A) Behavioral-Quantitative (C)
Brock et al. 2015	Interview and Observation	Attitudinal-Qualitative (A) Behavioral-Qualitative (B)
Kratz et al. 2010 Liang et al. 2012 Schirmer et al. 2015 Einfeldt and Degbelo 2021	Questionnaire and Data logger	Attitudinal-Quantitative (D) Behavioral-Quantitative (C)
Rehman and Cao 2016 Rehman and Cao 2017	Questionnaire and Cognitive Map	Attitudinal-Quantitative (D) Behavioral-Qualitative (B)
Brata et al. 2017 Brata and Liang 2019 Drewlow et al. 2022 Vincent et al. 2022	Questionnaire and Observation	Attitudinal-Quantitative (D) Behavioral-Qualitative (B)
Delikostidis and van Elzakker 2011 Abreu and Moraes 2012 Bernelind 2015 Schnitzler and Holscher 2015 Zahabi and Kaber 2018 Nadzir et al. 2019	Questionnaire and Thinking Aloud	Attitudinal-Quantitative (D) Attitudinal-Qualitative (A)
Rehrl et al. 2013 Noh et al. 2015 Goh et al. 2016 Chu et al. 2017 Brata and Liang 2020 Fogli et al. 2020 Matsuo et al. 2020 Sanjaya et al. 2020 Sharin et al. 2020 Brata et al. 2021 Swobodzinski et al. 2021 Nair et al. 2022	Questionnaire and Interview	Attitudinal-Quantitative (D) Attitudinal-Qualitative (A)

Table 1. Data collection methods and combinations used in the selected studies (n = 53). The table continues on the next page.

Article(s)	Method(s)	Correspondence with the framework (Figure 1)
Ramsay et al. 2010 Rehrl et al. 2012 Skulimowski et al. 2019 Qiu et al. 2024	Questionnaire, Interview, and Data Logger	Attitudinal-Quantitative (D) Attitudinal-Qualitative (A) Behavioral-Quantitative (C)
Kim and Song 2014 Grubert et al. 2015	Questionnaire, Interview, and Observation	Attitudinal-Quantitative (D) Attitudinal-Qualitative (A) Behavioral-Qualitative (B)
Delikostidis et al. 2016	Questionnaire, Interview, Thinking Aloud, and Cognitive Mapping	Attitudinal-Quantitative (D Attitudinal-Qualitative (A) Behavioral-Qualitative (B)
Wenig et al. 2016	Questionnaire, Interview, Thinking Aloud, and Observation	Attitudinal-Quantitative (D) Attitudinal-Qualitative (A) Behavioral-Qualitative (B)
van Elzakker and Delikostidis 2010	Questionnaire, Interview, Thinking Aloud, Cognitive Mapping, and Observation	Attitudinal-Quantitative (D) Attitudinal-Qualitative (A) Behavioral-Qualitative (B)
Dong et al. 2021	Questionnaire, Interview, Eye Tracking, and Cognitive Mapping	Attitudinal-Quantitative (D) Attitudinal-Qualitative (A) Behavioral-Qualitative (B)
Rehrl et al. 2014 Aditya et al. 2018 Diao and Shih 2018	Questionnaire, User Observation, and Data Logger	Attitudinal-Quantitative (D) Behavioral-Qualitative (B) Behavioral-Quantitative (C)

Table 1 (continued). Data collection methods and combinations used in the selected studies (n = 53).

The majority of studies (approximately 70%) employ a combination of two or more methods, employing hybrid approaches to capture both self-reported attitudes and observed behaviors. This phenomenon is indicative of the intricacies inherent in mobile mapping, where dynamic contexts (e.g., indoor/outdoor, in motion) and multimodal interactions necessitate a holistic approach, transcending the constraints imposed by individual methodologies.

CRITICAL ANALYSIS

After examining our set of studies, we identified several recurring patterns in the evaluation approaches adopted by the selected studies. The following analysis highlights the main methodological trends, their strengths, and their limitations, with particular attention to their implications for evaluating interactions with mobile digital maps.

- **Strong predominance of attitudinal approaches:** The preponderance of combinations utilizing attitudinal methods (D and A quadrants), predominantly questionnaires plus an interview or think-aloud protocol, signifies a pronounced prioritization of collecting subjective perceptions and verbal reports from users. While appropriate in exploratory phases, these methods tend to under-record real behaviors in highly variable environments—a central and challenging aspect of interaction with mobile digital maps. Verbal protocols are subject to the interpretation of researchers and necessitate extensive analysis of substantial qualitative data sets, which can compromise the objectivity and reproducibility of the results.

- **Frequent use of observational and instrumental methods in field studies:** The methods of user observation, data loggers, and, to a lesser extent, eye tracking appeared most frequently in studies conducted in the field (either entirely outdoors or an indoor/outdoor hybrid). This pattern suggests a recognition of the importance of ecological validity in the evaluation of moving maps. In these contexts, the dynamic environment (i.e., movement, variable lighting, distractions, body orientation, and GPS interference) exerts a substantial influence on user performance and experience.

MAIN METHODOLOGICAL LIMITATIONS IDENTIFIED

The systematic review not only identified the methods most frequently used in the evaluation of mobile digital maps but also revealed methodological limitations. The main limitations identified are presented below.

- **Very small sample sizes:** Most studies had sample sizes between 10 and 20 participants, with the most common methodological combination (DA) presenting a median of 12 participants. These relatively small samples were often influenced by Nielsen's 5-participant rule, which can be particularly problematic in highly heterogeneous and cognitively demanding mobile contexts.

- **Low representation of purely behavioral-quantitative methods:** Few studies relied on methods from the C quadrant of Figure 1. A more intensive use of logs, interaction metrics, prolonged eye-tracking, trajectory analysis, etc., could offer more objective indicators and be less biased by verbal reports.

KEY IMPLICATIONS AND POTENTIAL CONTRIBUTIONS

The results demonstrate that the evaluation of mobile digital maps presents methodological challenges that differ from those typically found in static cartography and conventional interface evaluation. Unlike traditional map studies, which are commonly conducted in controlled environments with relatively standardized interactions, mobile map evaluations must account for dynamic factors such as user movement, indoor and outdoor transitions, GPS variability, environmental distractions, and increased cognitive load. These characteristics were reflected in the predominance of hybrid evaluation methods, the frequent use of field studies, and the tendency for larger or more adaptive sample sizes when behavioral observations or passive data collection were incorporated. Based on these findings, the results point to the need for:

- A more systematic adoption of hybrid qualitative/quantitative methodologies

- Increased field testing in real-world map usage situations, especially in situations with high contextual variability.

- The development of specific guidelines and methodological frameworks adapted to the particularities of mobile cartography (dynamic environment, use while in motion, small screens, multimodality, external interferences).

RESULTS AND DISCUSSION

THE VALUE OF MIXED METHODS

Our recommended mixed-methods approach integrates quantitative data (e.g., satisfaction scales, performance, and perceptions via questionnaire) with qualitative data (e.g., detailed reports of cognitive difficulties, navigation strategies, and frustrations via interview or think-aloud protocol). The triangulation process enables the collection of more diverse and robust data, particularly in dynamic mobile contexts. In such environments, factors such as movement, frequent interruptions, and high cognitive load can impede the detection of usability problems (Bartling et al. 2021). However, attitudinal methods remain limited when not also complemented by objective passive recording of behavioral data (e.g., a data logger, quadrant C, Figure 1), which automatically capture information available on the device itself, such as coordinates of the traveled route, acceleration, number and location of screen touches, ambient noise, among others. These sorts of data, despite their richness and objectivity, are frequently neglected by evaluators. As a result, the ability to understand the user's actual behavior in the field is diminished.

The prevalence of DA combinations, such as a questionnaire plus some sort of verbalization (interview, focus group, etc.), signifies that researchers in mobile mapping acknowledge the constraints of purely quantitative or qualitative methodologies when conducting studies in the

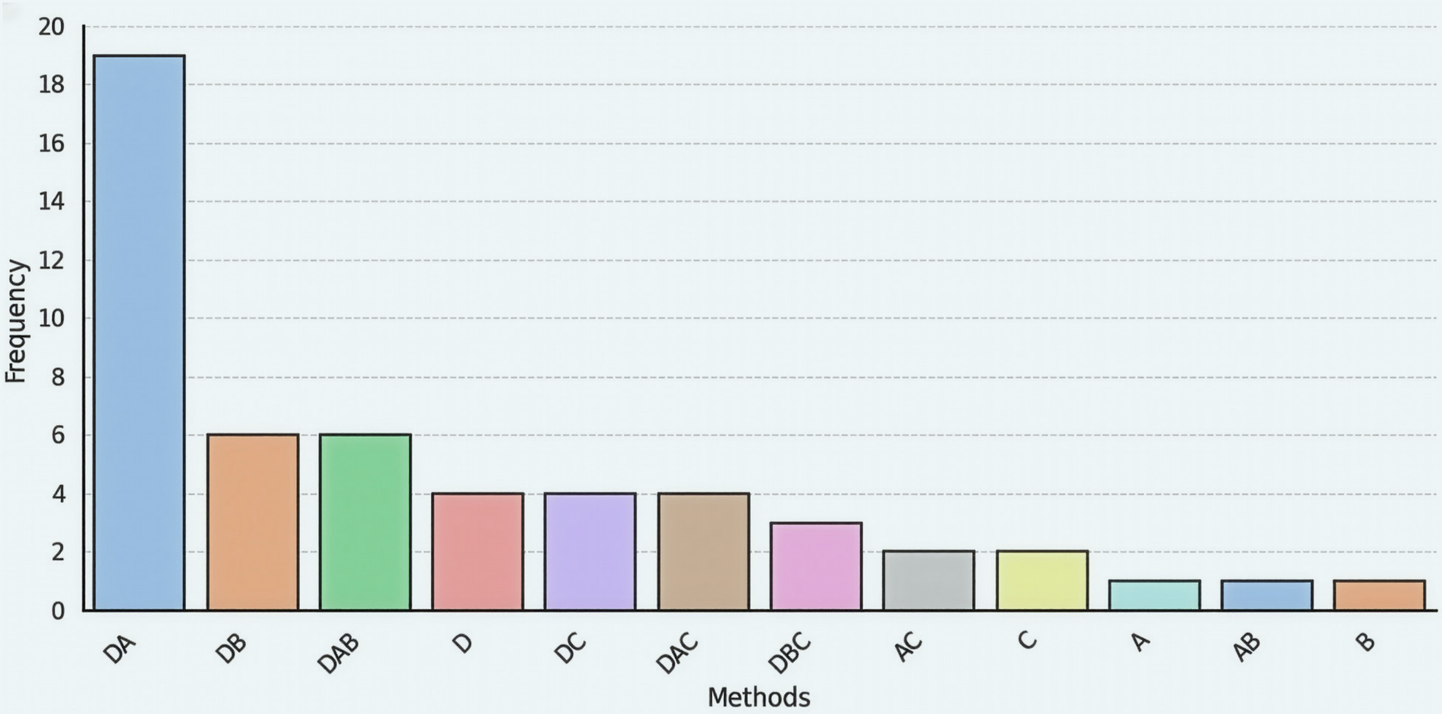

Figure 2. Methods used in evaluations of mobile digital maps.

inherently variable environment of digital maps on mobile devices. In contrast to static or large-screen maps, mobile maps are characterized by dynamic contexts, such as pedestrian navigation in real environments, transitions between indoor and outdoor spaces, and variations in lighting and GPS accuracy. These dynamic contexts contribute to increased variability in behavioral and perceptual data. The employment of mixed methods facilitates triangulation, thereby enhancing the detection of contextual problems that may be underestimated by conventional heuristics such as Nielsen's (1993).

This trend indicates the emergence of new methodologies in mobile mapping, such as hybrid (laboratory + field) or longitudinal "in-the-wild" assessments. These methodologies have the potential to more accurately capture the impact of the user's context (activity, physical environment, emotional state) on map design and usability (Bartling et al. 2021).

NUMBER OF PARTICIPANTS

Figure 3 presents boxplots illustrating the distribution of the number of participants as a function of the methodological combinations of data collection, categorized according to the grid in Figure 1.

Figure 3 reveals striking differences, such as the fact that many isolated methods tend to use smaller samples (except for isolated questionnaires), while mixed combinations, especially those that include observation or passive recording, require larger samples to capture the variability typical of moving map assessments.

The observed medians and ranges highlight clear variations between the approaches:

- **A (Isolated Interview)**: 12 participants (n = 1).
- **B (Isolated Observation)**: 12 participants (n = 1).
- **C (Isolated Data Logger)**: median = 8 (range 1–15, n = 2).
- **D (Isolated Questionnaire)**: median = 42 (range 5–120, n = 4).
- **DA (Questionnaire + Verbalization)**: median = 12 (range 1–50, n = 19).
- **DAB (Questionnaire + Verbalization + Observation/Cognitive Map/Eye Tracking)**: median = 20 (range 8–40, n = 6).

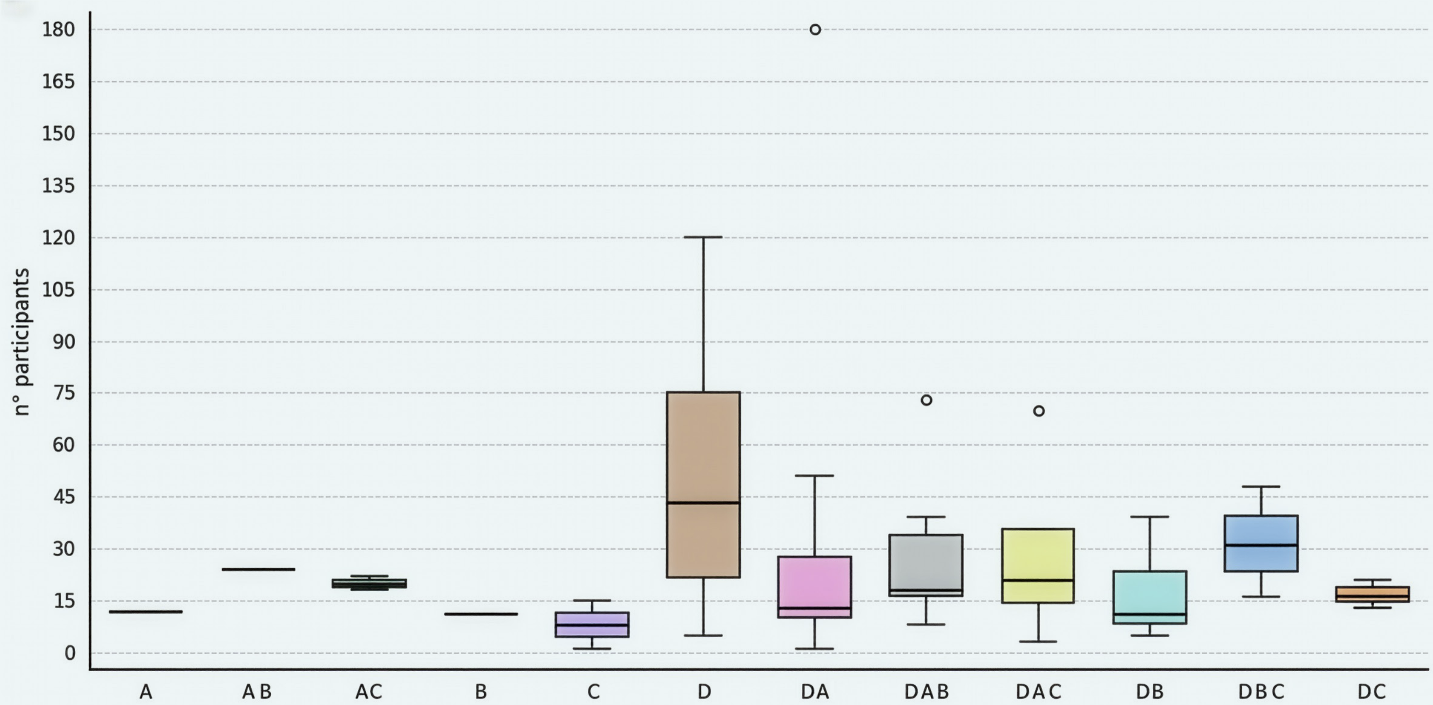

Figure 3. Relationship between the number of participants and the data collection methods.

- **DAC (Questionnaire + Verbalization + Passive Recording)**: median ≈ 23 (range 5–35, n = 4).
- **DB (Questionnaire + Observation/Cognitive Map)**: median = 13 (range 8–40, n = 6).
- **DBC (Questionnaire + Observation + Data Logger)**: median = 32 (range 16–48, n = 3).
- **DC (Questionnaire + Data Logger)**: median = 18 (range 12–22, n = 4).

The boxplots in Figure 3 reveal asymmetrical distributions across several groups, with positive outliers (exceptionally large samples) primarily in predominantly quantitative methods (isolated D) or mixed methods with passive recording (i.e., data logger) components (DA, DAB, and DAC). These outliers frequently correspond to studies that prioritize field performance metrics or robust statistical validation.

This pattern indicates the potential for methodologies that are more adaptable to mobile mapping. These methodologies could include a sample size of 5–12 participants in qualitative laboratory tests to identify interface problems, followed by validation with larger samples (20–40, or more) in outdoor field studies, where environmental variability is high. Research conducted with a sample size of 5–8 participants, as indicated by Nielsen, can be expeditious in identifying significant flaws. However, this approach may underestimate subtle variations associated with spatial and behavioral contexts.

ASSESSMENT CONTEXT

In addition to the combination of methods, the context of the assessments also significantly influences the sample size. Figure 4 examines the relationship between the number of participants and key contextual variables, including the presence or absence of a moderator, the type of target audience (diverse or specific), and the location (indoor, outdoor, or hybrid indoor/outdoor).

The following is a summary of the results presented in Figure 4:

- **Moderation**
  - Moderated: median = 20 (range 1–50, n = 50)
  - Unmoderated: median = 23 (range 15–120, n = 3)
- **Target audience**
  - Diversified (i.e., general population): median = 20 (range 1–75, n = 39)

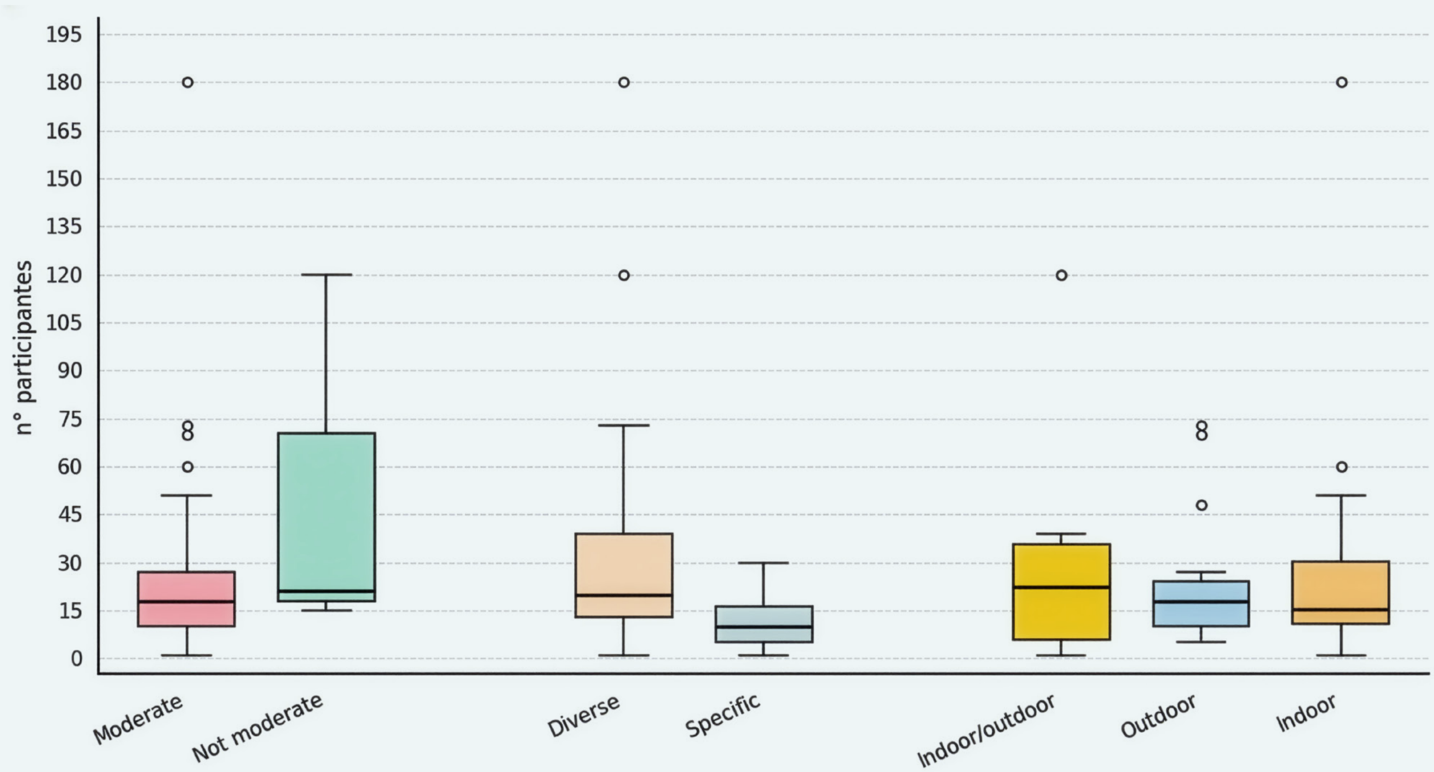

Figure 4. Relationship between the number of participants and the context of the assessments.

- Specific (e.g., specialists, elderly, visually impaired): median = 10 (range 1–33, n = 14)

- **Location of the assessment**
  - Internal (laboratory/controlled): median = 20 (range 1–50, n = 28)
  - Outdoor (field): median = 15 (range 10–28, n = 19)
  - Indoor/outdoor use: median = 22 participants (range: 1–120; n = 6 studies).

The reviewed studies included assessments conducted in laboratory, outdoor, and hybrid indoor/outdoor environments, with laboratory studies being the most common (n = 28), followed by outdoor studies (n = 19) and hybrid studies (n = 6). This distribution highlights the continued importance of controlled environments while also demonstrating a substantial use of real-world settings to evaluate mobile map interactions under realistic conditions. Although the observed median number of participants was lower in outdoor studies than in laboratory studies (15 vs. 20 participants), this comparison is descriptive only, as no inferential statistical analysis was performed. The lower median observed in field studies may reflect the greater logistical complexity and environmental variability associated with outdoor experiments.

While outdoor environments demonstrate a lower median value, they exhibit a more constrained range, indicating that field studies place a premium on acquiring sufficient samples to detect consistent effects despite the presence of substantial environmental variability. This variability may include factors such as lighting conditions, noise disturbances, inaccurate GPS, and movement patterns. Conversely, indoor tests permit greater control and, consequently, larger or more flexible samples. However, the ecological validity of the collected data is lower.

This distinction underscores the necessity of contextual approaches for mobile digital maps, such as the hybrid approach we advocated for earlier. Laboratory (indoor) methods can rely on smaller samples for the initial detection of interface problems, while field (outdoor) studies benefit from moderate to larger samples (15–30, or more) to validate performance under real-world conditions. The observed preference for uncontrolled environments underscores the significance of ecological validity in the context of mobile mapping. This aspect distinguishes mobile mapping from the evaluation of traditional static maps.

Figure 5 presents a heatmap that delineates the number of participants according to the evaluation method and whether the participant pool was diverse (with a sample of the general public) or specific (including specialists, the elderly, visually impaired individuals, and groups with predefined criteria).

As illustrated in Figure 5, the audience profile emerges as a pivotal factor in determining the requisite sample size, in conjunction with the methodological approach. Evaluations with specific types of participants often adopt small samples (often fewer than 10) to allow for in-depth analysis, a common practice in accessibility or niche studies (e.g., navigation for visually impaired users). In the presence of more heterogeneous audiences, the sample sizes tend to increase substantially in mixed methods that utilize logging or observation (e.g., DAC studies had up to 35 participants). This phenomenon underscores the necessity for representativeness in order to generalize findings in real-world mobile usage contexts.

Figure 6 provides a synopsis of the aggregated dataset from the 53 selected studies, presenting the mean number of participants per test application context, in addition to the minimum and maximum values observed. The organization of the samples by specific test characteristics (method, moderation, type of audience, and indoor/outdoor environment) allows for the visualization of the overall variability of the samples and the identification of clear trends in the literature on the evaluation of mobile digital maps.

The trends summarized in Figure 6 reinforce the patterns identified in the previous analyses and highlight how sample size varies according to methodological and contextual factors. The main findings include:

- Smaller samples (medians 8–15) predominate in isolated qualitative methods (A, B, C) or simple mixed methods (DA, DB) studies, especially those with specific populations or controlled laboratory tests.
- Larger samples (medians 20–40, or more) occur in studies with isolated quantitative methods (D), complex mixed combinations (DAB, DBC, DAC), and assessments with diverse audiences or in non-moderated/field contexts.

Method (Context)	Number of Participants								
	< 10	10–19	20–29	30–39	40–49	50–59	60–79	80–99	≥ 100
A (Diversified)	0	1	0	0	0	0	0	0	0
A (Specific)	0	0	0	0	0	0	0	0	0
AB (Diversified)	0	0	0	0	0	0	0	0	0
AB (Specific)	0	0	1	0	0	0	0	0	0
AC (Diversified)	0	0	0	0	0	0	0	0	0
AC (Specific)	0	1	1	0	0	0	0	0	0
B (Diversified)	0	0	0	0	0	0	0	0	0
B (Specific)	0	1	0	0	0	0	0	0	0
C (Diversified)	1	1	0	0	0	0	0	0	0
C (Specific)	0	0	0	0	0	0	0	0	0
D (Diversified)	1	0	1	0	0	0	1	0	1
D (Specific)	0	0	0	0	0	0	0	0	0
DA (Diversified)	0	4	4	0	2	1	0	0	1
DA (Specific)	4	2	0	1	0	0	0	0	0
DAB (Diversified)	1	3	0	1	0	0	1	0	0
DAB (Specific)	0	0	0	0	0	0	0	0	0
DAC (Diversified)	0	1	1	0	0	0	1	0	0
DAC (Specific)	1	0	0	0	0	0	0	0	0
DB (Diversified)	1	1	1	1	0	0	0	0	0
DB (Specific)	1	1	0	0	0	0	0	0	0
DBC (Diversified)	0	1	0	1	1	0	0	0	0
DBC (Specific)	0	0	0	0	0	0	0	0	0
DC (Diversified)	0	3	1	0	0	0	0	0	0
DC (Specific)	0	0	0	0	0	0	0	0	0

Figure 5. Relationship between participant sample-size categories, evaluation methods, and participant characteristics. Each cell represents the number of studies identified for a given combination of evaluation method, participant profile, and sample-size category. Darker shades indicate higher frequencies of studies, whereas lighter shades indicate lower frequencies.

- Outdoor (field) settings tend to have narrower and moderate median ranges (≈15), reflecting logistical challenges, while indoor environments allow for greater flexibility (up to 50–120 in quantitative cases).

As seen in Figure 6, the number of participants in mobile digital map evaluations does not adhere to a universal recommendation; rather, it is strongly determined by the study's objective and the specific demands of mobile use, such as navigation on the go, indoor-outdoor transitions, environmental variability, and high cognitive load.

Contrary to conventional cartography, which is primarily tested in laboratory-based settings and utilizes more standardized samples, mobile maps necessitate adaptive methodologies to capture real-world behaviors in scenarios that are inherently unpredictable.

Current practices, which typically utilize samples of between 10 and 30 participants, exceed the stringent application of Nielsen's heuristic (1993). These practices have proven effective in identifying significant usability issues; however, their capacity for generating robust

Groups	Public		Experiment		Data			Location			n	n° of participants		
	Diversified	Specific	Moderate	Not moderate	Quantitative	Qualitative	Quantitative and Qualitative	Indoor	Outdoor	Indoor & Outdoor		Average	Minimum	Maximum
DA	■		■				■			■	9	22	20	25
DA		■	■				■			■	1	1	1	1
DA	■		■				■	■			9	80	13	180
DA		■	■				■	■			1	15	5	30
DA	■		■				■		■		1	17	10	24
DA	■		■		■			■			1	51	51	51
DA		■	■				■		■		1	10	10	10
DA	■		■				■	■			1	25	10	41
DB		■		■			■		■		2	5	5	5
DB		■	■				■		■		1	9	8	10
D	■		■				■	■			1	120	120	120
D	■			■			■			■	1	27	27	27
D	■		■		■				■		2	32	5	60
AC		■	■		■			■			1	22	22	22
AC		■	■				■	■			1	18	18	18
DAC	■		■				■		■		2	44	18	70
DAC		■	■				■	■			1	3	3	3
C	■		■		■			■			1	1	1	1
C	■			■	■			■			1	15	15	15
DBC	■		■				■	■			1	31	31	31
DBC	■		■				■		■		1	32	16	48
DAB	■		■				■		■		1	33	8	73
DAB	■		■				■			■	1	39	39	39
DAB	■		■				■	■			1	17	16	18
A	■		■			■		■			1	12	12	12
AB		■	■				■	■			1	24	24	24
DC	■		■		■			■			1	15	13	18
DC	■			■	■				■		1	21	21	21
B		■	■			■		■			1	11	11	11

Figure 6. Number of participants in relation to the application context of the test sets.

generalizations across diverse audiences or complex tasks is limited. The extant literature on mobile mapping thus leads us to suggest an innovative combination of methodologies. First, a small sample size (5–12) should be used in qualitative laboratory tests to initially detect interface flaws. Second, a moderate to large sample size (15–40, or more) should be used in outdoor or hybrid field studies that incorporate passive logging and observation to achieve greater statistical power and ecological validity. Third, longitudinal "in-the-wild" strategies or context-adaptive samples (e.g., automatic indoor/outdoor adjustment) should be explored to reduce the cognitive load on participants related to the test while capturing real-world map use.

CONCLUSION

In this study, we conducted a meta-analysis of 53 articles published between 2010 and 2024, analyzing the number of participants in evaluations of digital maps accessed via mobile devices. The findings indicate that the number of participants is contingent upon the data collection method, the target audience profile, and the application context (laboratory vs. field, indoor vs. outdoor).

The predominant combination identified in the extant literature involves the implementation of a questionnaire in conjunction with either an interview or a thought verbalization protocol (DA), typically involving 10–20 participants. Mixed methods that incorporate behavioral observation, cognitive mapping, or passive recording (e.g., DAB, DBC, DAC) tend to require larger samples (medians 20–32, or more), reflecting the need for greater statistical power and triangulation to deal with the variability inherent in mobile use (navigation on the go, indoor-outdoor transitions, environmental distractions, and high cognitive load).

Contrary to conventional cartography, which is frequently examined using controlled environments and standardized samples, the evaluation of mobile digital maps necessitates adaptive approaches to capture real-world behaviors in dynamic and unpredictable scenarios. Although contemporary practices exceed the inflexible implementation of Nielsen's heuristic (1993), small samples remain predominantly effective for detecting significant usability issues. However, their capacity for producing reliable generalizations across diverse audiences or complex tasks is constrained.

Our findings lead us to suggest practical recommendations for future mobile mapping assessments:

- Start with small samples (5–12 participants) in qualitative laboratory tests to identify interface failures.
- Validate with moderate to larger samples (15–40, or more) in outdoor or hybrid field studies, incorporating passive data logging and user observation to increase the ecological validity and statistical power of the analyses.
- Explore longitudinal "in-the-wild" methodologies or context-adaptive samples (e.g., changes in indoor/outdoor environments), altering the participant's cognitive demands while capturing data close to the actual use of the map.

These contextualized guidelines contribute to the advancement of mobile cartography by being more aligned with the specific needs of evaluating maps accessed by mobile devices.

We recognize that our study is limited by its narrow focus on articles that dealt only with navigation tasks, as well as the paucity of longitudinal studies within the examined sample. These limitations suggest future research directions involving the integration of smartphone sensor data (e.g., GPS, accelerometers, gyroscopes, and interaction logs) with artificial intelligence methods for the large-scale analysis of user behavior during real-world navigation. Such approaches could provide more objective and context-aware evaluations of mobile digital maps.

REFERENCES

Abreu, Leonardo, and Anamaria de Moraes. 2012. "Point Navigation Map Method to Track Low-income Mobile User's Interaction." *WORK: A Journal of Prevention, Assessment & Rehabilitation* 41(1): 3438–42. **https://doi.org/10.3233/WOR-2012-0621-3438**.

Aditya, Trias, Dany Laksono, Heri Sutanta, Nur Izzahudin, and Febrian F. Susanta. 2018. "A Usability Evaluation of a 3D Map Display for Pedestrian Navigation." *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XLII-4/W10: 3–10. **https://doi.org/10.5194/isprs-archives-XLII-4-W10-3-2018**.

Bartling, Mona, Anthony C. Robinson, Bernd Resch, Anton Eitzinger, and Karl Atzmanstorfer. 2021. "The Role of User Context in the Design of Mobile Map Applications." *Cartography and Geographic Information Science* 48 (5): 432–48. **https://doi.org/10.1080/15230406.2021.1933595**.

Bernelind, Sarah. 2015. "Navigation in Augmented Reality." MSc Thesis, KTH Royal Institute of Technology. **https://www.diva-portal.org/smash/record.jsf?pid=diva2:850246**.

Bitsch Link, Jó Ágila, Paul Smith, Nicolai Viol, and Klaus Wehrle. 2012. "Accurate Map-Based Indoor Navigation on the Mobile." *Journal of Location Based Services* 7 (1): 23–43. **https://doi.org/10.1080/17489725.2012.692620**.

Brade, Jennifer, Mario Lorenz, Marc Busch, Niels Hammer, Manfred Tscheligi, and Philipp Klimant. 2017. "Being There Again – Presence in Real and Virtual Environments and its Relation to Usability and User Experience Using a Mobile Navigation Task." *International Journal of Human-Computer Studies* 101: 76–87. **https://doi.org/10.1016/j.ijhcs.2017.01.004**.

Brata, Komang C., and Deron Liang. 2019. "An Effective Approach to Develop Location-based Augmented Reality Information Support." *International Journal of Electrical and Computer Engineering* 9 (4): 3060–68. **http://doi.org/10.11591/ijece.v9i4.pp3060-3068**.

———. 2020. "Comparative Study of User Experience on Mobile Pedestrian Navigation Between Digital Map Interface and Location-based Augmented Reality." *International Journal of Electrical and Computer Engineering* 10 (2): 2037–44. **https://doi.org/10.11591/ijece.v10i2.pp2037-2044**.

Brata, Komang C., Aryo Pinandito, Mahardeka T. Ananta, and Nirizal D. Priandani. 2017. "Design of Public Transportation Navigation System on Android Wear Device." In *2017 International Conference on Sustainable Information Engineering and Technology*, 385–91. Malang, Indonesia: IEEE. **http://doi.org/10.1109/SIET.2017.8304169**.

Brata, Komang C., Aryo Pinandito, Nurizal D. Priandani, and Mahardeka T. Ananta. 2021. "Usability Improvement of Public Transit Application Through Mental Model and User Journey." *TELKOMNIKA (Telecommunication Computing Electronics and Control)* 19 (2): 397–405. **http://doi.org/10.12928/telkomnika.v19i2.18323**.

Brock, Anke M., Philippe Truillet, Bernard Oriola, Delphine Picard, and Christophe Jouffrais. 2014. "Interactivity Improves Usability of Geographic Maps for Visually Impaired People." *Human–Computer Interaction* 30 (2): 156–94. **https://doi.org/10.1080/07370024.2014.924412**.

Chu, Chung-Hua, Shu-Lin Wang, and Bi-Chi Tseng. 2017. "Mobile Navigation Services with Augmented Reality." *IEEJ Transactions on Electrical and Electronic Engineering* 12 (S1): 95–103. **https://doi.org/10.1002/tee.22443**.

Çöltekin, Arzu, Susanne Bleisch, Gennady Andrienko, and Jason Dykes. 2017. "Persistent Challenges in Geovisualization – A Community Perspective." *International Journal of Cartography* 3 (sup1): 115–39. **https://doi.org/10.1080/23729333.2017.1302910**.

Darvishy, Alireza, Hans-Peter Hutter, Markus Grossenbacher, and Dario Merz. 2020. "Touch Explorer: Exploring Digital Maps for Visually Impaired People." In *Computers Helping People with Special Needs: 17th International Conference, ICCHP 2020,* edited by Klaus Miesenberger et al., 427–34. Lecco, Italy. Springer. **https://doi.org/10.1007/978-3-030-58796-3_50**.

Delikostidis, Ioannis, and Corné P. J. M. van Elzakker. 2011. "Usability testing of a prototype mobile navigation interface for pedestrians." Paper presented at the 25th International Cartographic Conference, Paris, July 3–8. **http://hdl.handle.net/10092/10595**.

Delikostidis, Ioannis, Corné P. J. M. van Elzakker, and Menno-Jan Kraak. 2016. "Overcoming Challenges in Developing More Usable Pedestrian Navigation Systems." *Cartography and Geographic Information Science* 43 (3): 189–207. **https://doi.org/10.1080/15230406.2015.1031180**.

Diao, Pei-Huang, and Naai-Jung Shih. 2018. "MARINS: A Mobile Smartphone AR System for Pathfinding in a Dark Environment." *Sensors* 18 (10): 3442. **https://doi.org/10.3390/s18103442**.

Dirin, Amir, Teemu H. Laine, and Ari Alamäki. 2018. "Managing Emotional Requirements in a Context-Aware Mobile Application for Tourists." *International Journal of Interactive Mobile Technologies* 12 (2): 177–96. **https://doi.org/10.3991/ijim.v12i2.7933**.

Drewlow, Joshua, Michael Däppen, and Michael Lehmann. 2022. "Navigation with Augmented Reality in a Hospital." In *Healthcare of the Future 2022,* edited by Thomas Bürkle, Kerstin Denecke, Jürgen Holm, Murat Sariyar, and Michael Lehmann, 111–14. IOS Press. **https://doi.org/10.3233/SHTI220335**.

Dong, Weihua, Tianyu Yang, Hua Liao, and Liqiu Meng. 2020. "How Does Map Use Differ in Virtual Reality and Desktop-Based Environments?" *International Journal of Digital Earth* 13 (12): 1484–503. **https://doi.org/10.1080/17538947.2020.1731617**.

Dong, Weihua, Yulin Wu, Tong Qin, Xinran Bian, Yan Zhao, Yanrou He, Yawei Xu, and Cheng Yu. 2021. "What Is the Difference between Augmented Reality and 2D Navigation Electronic Maps in Pedestrian Wayfinding?" *Cartography and Geographic Information Science* 48 (3): 225–40. **https://doi.org/10.1080/15230406.2021.1871646**.

Einfeldt, Lasse, and Auriol Degbelo. 2021. "User Interface Factors of Mobile UX: A Study with an Incident Reporting Application." In *Proceedings of the 16th International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications*, vol. 2, 245–54. SCITEPRESS. **https://doi.org/10.5220/0010325302450254**.

Eraslan, Sukru, Yeliz Yesilada, and Simon Harper. 2016. "Eye Tracking Scanpath Analysis on Web Pages: How Many Users?" In *Proceedings of the Ninth Biennial ACM Symposium on Eye Tracking Research & Applications*, 103–110. ACM. **https://doi.org/10.1145/2857491.2857519**.

Fogli, Daniela, Alberto Arenghi, and Fulvio Gentilin. 2020. "A Universal Design Approach to Wayfinding and Navigation." *Multimedia Tools and Applications* 79 (45): 33577–601. **https://doi.org/10.1007/s11042-019-08492-2**.

Goh, Dion H., Chei S. Lee, and Khasfariyati Razikin. 2016. "Interfaces for Accessing Location-Based Information on Mobile Devices: An Empirical Evaluation." *Journal of the Association for Information Science and Technology* 67 (12): 2882–96. **https://doi.org/10.1002/asi.23566**.

Grubert, Jens, Michel Pahud, Raphael Grasset, Dieter Schmalstieg, and Hartmut Seichter. 2015. "The Utility of Magic Lens Interfaces on Handheld Devices for Touristic Map Navigation." *Pervasive and Mobile Computing* 18: 88–103. **https://doi.org/10.1016/j.pmcj.2014.08.005**.

Horbinski, Tymoreusz. 2019. "Progressive Evolution of Designing Internet Maps on the Example of Google Maps." *Geodesy and Cartography* 68 (1): 177–90. **https://doi.org/10.24425/gac.2019.126095**.

Kim, Huhn, and Haewon Song. 2014. "Evaluation of the Safety and Usability of Touch Gestures in Operating in Vehicle Information Systems with Visual Occlusion." *Applied Ergonomics* 45 (3): 789–98. https://doi.org/10.1016/j.apergo.2013.10.013.

Kratz, Sven, Ivo Brodien, and Michael Rohs. 2010. "Semi-Automatic Zooming for Mobile Map Navigation." In *Proceedings of the 12th International Conference on Human-Computer Interaction with Mobile Devices and Services*, 63–72. https://doi.org/10.1145/1851600.1851615.

Liang, Hai-Ning, James Trenchard, Myron Semegen, and Pourang Irani. 2012. "An Exploration of Interaction Styles in Mobile Devices for Navigating 3D Environments." In *Proceedings of the 10th Asia Pacific Conference on Computer Human Interaction*, 309–13. ACM. https://doi.org/10.1145/2350046.2350062.

Lu, Fangfang, Hao Zhou, Lingling Guo, Jingjing Chen, and Licheng Pei. 2021. "An ARCore-Based Augmented Reality Campus Navigation System." *Applied Sciences* 11 (160): 7515. https://doi.org/10.3390/app11167515.

Maly, Ivo, Zdenek Mikovec, Jan Vystrcil, Jakub Franc, and Pavel Slavik. 2013. "An Evaluation Tool for Research of User Behavior in a Realistic Mobile Environment." *Personal and Ubiquitous Computing* 17 (1): 3–14. https://doi.org/10.1007/s00779-011-0475-0.

Martins, Vinicius Bergmann, Fabrício Rosa Amorim, Marcio Augusto Reolon Schmidt, and Luciene Stamato Delazari. 2023. "Study About the Appropriate Number of Participants in Map User Studies." *International Journal of Cartography* 9 (2): 196–209. https://doi.org/10.1080/23729333.2022.2163142.

Matsuo, Masaki, Takahiro Miura, Ryosuke Ichikari, Karimu Kato, and Takehi Kurata. 2020. "OTASCE Map: A Mobile Map Tool with Customizable Audio-Tactile Cues for the Visually Impaired." *Journal on Technology and Persons with Disabilities* 8: 82–103. http://hdl.handle.net/10211.3/215981.

Montuwy, Angélique, Béatrice Cahour, and Aurélie Dommes. 2019. "Using Sensory Wearable Devices to Navigate the City: Effectiveness and User Experience in Older Pedestrians" *Multimodal Technologies and Interaction* 3 (1): 17. https://doi.org/10.3390/mti3010017.

Nadzir, Maslinda, Azham Hussain, Emmanuel O. C. Mkpojiogu, Josephine O. Faromiki, and Eman M. A. Abdusalam. 2019. "The Effectiveness and Efficiency of a GPS Route and Voice Navigation App." *International Journal of Innovative Technology and Exploring Engineering* 8 (8S): 425–27. https://www.ijitee.org/portfolio-item/H10730688S19/.

Nair, Vishnu, Greg Olmschenk, William H. Seiple, and Zhigang Zhu. 2020. "ASSIST: Evaluating the Usability and Performance of an Indoor Navigation Assistant for Blind and Visually Impaired People." *Assistive Technology* 34 (3): 289–99. https://doi.org/10.1080/10400435.2020.1809553.

Nielsen, Jakob. 1993. *Usability Engineering*. Academic Press.

Noguera, José M., Manuel J. Barranco, Rafael J. Segura, and Luis Martínez. 2012. "A Mobile 3D-GIS Hybrid Recommender System for Tourism." *Information Sciences* 215: 37–52. https://doi.org/10.1016/j.ins.2012.05.010.

Noh, GeeYoung, DongNyeok Jeong, Sangsun Park, and Jundong Cho. 2015. "Design Guideline on Location Based User Emotion Sharing Map Service." In *HCI International 2015 - Posters' Extended Abstracts*, edited by Constantine Stephanidis, 5140018. Springer. https://doi.org/10.1007/978-3-319-21383-5_86.

Prandi, Catia, Barbara R. Barricelli, Silvia Mirri, and Daniela Fogli. 2023. "Accessible Wayfinding and Navigation: A Systematic Mapping Study." *Universal Access in the Information Society* 22 (1): 185–212. https://doi.org/10.1007/s10209-021-00843-x.

Qiu, Xiaohe, Zhen Yang, Jinxing Yang, Qijun Wang, and Duming Wang. 2024. "Impact of AR Navigation Display Methods on Wayfinding Performance and Spatial Knowledge Acquisition." *International Journal of Human–Computer Interaction* 40 (10): 2676–96. https://doi.org/10.1080/10447318.2023.2169524.

Ramsay, Andrew, Marilyn McGee-Lennon, Graham A. Wilson, Steven J. Gray, Philip Gray, and François De Turenne. 2010. “Tilt and go: exploring multimodal mobile maps in the field.” *Journal on Multimodal User Interfaces* 3: 167–77. https://doi.org/10.1007/s12193-010-0037-1.

Rehrl, Karl, Elisabeth Häusler, Renate Steinmann, Sven Leitinger, Daniel Bell, and Michael Weber. 2012. “Pedestrian Navigation with Augmented Reality, Voice and Digital Map: Results from a Field Study Assessing Performance and User Experience.” In *Advances in Location-Based Services*, edited by Georg Gartner and Felix Ortag, 3–20. Springer. https://doi.org/10.1007/978-3-642-24198-7_1.

Rehrl, Karl, Elisabeth Häusler, Sven Leitinger, and Daniel Bell. 2014. “Pedestrian Navigation with Augmented Reality, Voice and Digital Map: Final Results from an in situ Field Study Assessing Performance and User experience.” *Journal of Location Based Services* 8 (2): 75–96. https://doi.org/10.1080/17489725.2014.946975.

Rehrl, Karl., Simon Gröechenig, Hartwig Hochmair, Sven Leitinger, Renate Steinmann, and Andreas Wagner. 2013. “A Conceptual Model for Analyzing Contribution Patterns in the Context of VGI.” In *Progress in Location-based Services*, edited by Jukka M. Krisp, 373–88. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-34203-5_21.

Rehman, Umair, and Shi Cao. 2016. “Experimental Evaluation of Indoor Navigation Devices.” *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 59 (1): 1783–87. https://doi.org/10.1177/1541931215591385.

———. 2017. “Augmented-Reality-Based Indoor Navigation: A Comparative Analysis of Handheld Devices Versus Google Glass.” *IEEE Transactions on Human-Machine Systems* 47 (1): 140–51. https://doi.org/10.1109/THMS.2016.2620106.

Rohrer, Christian. 2022. “When to Use Which User-Experience Research Methods.” Nielsen Norman Group. July 17, 2022. https://www.nngroup.com/articles/which-ux-research-methods/.

Sakpere, Wilson E., Nhlanhla B. W. Mlitwa, and Michael A. Oshin. 2017. “Towards an Efficient Indoor Navigation System: A Near Field Communication Approach.” *Journal of Engineering, Design and Technology* 15 (4): 505–27. https://doi.org/10.1108/JEDT-10-2016-0073.

Sanjaya, M. Rudi, Dedy Kurniawan, and Ariansyah Saputra. 2020. “GIS Android mobile based Software Development for Tourism Objects, Public Places list, Transportations list, and Culinary Places list Using Usability Measurement.” *Journal of Physics: Conference Series* 1500 (1): 012117. https://doi.org/10.1088/1742-6596/1500/1/012117.

Schirmer, Maximilian, Johannes Hartmann, Sven Bertel, and Florian Echtler. 2015. “Shoe Me the Way: A Shoe-Based Tactile Interface for Eyes-Free Urban Navigation.” In *Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services*, 327–36. ACM. https://doi.org/10.1145/2785830.2785832.

Schmettow, Martin. 2012. “Sample Size in Usability Studies.” *Communications of the ACM* 55 (4): 64–70. https://doi.org/10.1145/2133806.2133824.

Schnitzler, Verena and Christoph Hölscher. 2015. “User Experience and Strategy Choices During Navigation: A Content Analysis of Navigators Using Different Types of Wayfinding Devices.” In *Proceedings of the EuroAsianPacific Joint Conference on Cognitive Science (EAPCogSci 2015)*, edited by Gabriella Airenti, Bruno G. Bara, and Giulio Sandini. CEUR Workshop Proceedings, vol. 1419. Torino, September 25–27. http://hdl.handle.net/20.500.11850/108591.

Shah, Hurmat A., Mowafa Househ, Jens Schneider, Dena A. Al-Thani, and Marco Agus. 2024. “Studying Usability of Public Health Surveillance Maps Through Framework Based Heuristic Evaluation.” *Computer Methods and Programs in Biomedicine Update* 5: 100143. https://doi.org/10.1016/j.cmpbup.2024.100143.

Sharin, Nursyahirah A., Noris M. Norowi, and Lili N. Abdullah. 2020. "A User Requirements Study for Developing Mobile-Based Augmented Reality Indoor Map Locator Application." *International Journal of Advanced Research in Engineering and Technology (IJARET)* 11 (12): 1361–73. **https://iaeme.com/Home/article_id/IJARET_11_12_129**.

Skulimowski, Piotr, Mateusz Owczarek, Andrzej Radecki, Michael Bujacz, Dariusz Rzeszotarski, and Paweł Strumiłło. 2019. "Interactive Sonification of U-Depth Images in a Navigation Aid for the Visually Impaired." *Journal on Multimodal User Interfaces* 13 (3): 219–30. **https://doi.org/10.1007/s12193-018-0281-3**.

Swobodzinski, Martin, Amy T. Parker, Julie D. Wright, Kyrsten Hansen, and Becky Morton. 2021. "Seamless Wayfinding by a Deafblind Adult on an Urban College Campus: A Case Study on Wayfinding Performance, Information Preferences, and Technology Requirements." *Frontiers in Education* 6: 723098. **https://doi.org/10.3389/feduc.2021.723098**.

van Elzakker, Corné P. J. M., and Ioannis Delikostidis. 2010. "Use, User, and Usability Research for Mobile Geo-Applications for Personal Orientation and Navigation." In *2010 IEEE International Professional Communication Conference (IPCC)*, 121–30. Piscataway, NJ: IEEE. **https://doi.org/10.1109/IPCC.2010.5529824**.

van Elzakker, Corné P. J. M., Ioannis Delikostidis, and Peter J. M. van Oosterom. 2008. "Field-Based Usability Evaluation Methodology for Mobile Geo-Applications." *The Cartographic Journal* 45 (2): 139–49. **https://doi.org/10.1179/174327708X305139**.

Vincent, Claude, Rébecca Girard, Frédéric Dumont, Philippe Archambault, François Routhier, and Mir Abolfazl Mostafavi. 2022. "Evaluation of Satisfaction with Geospatial Assistive Technology (ESGAT): A Methodological and Usability Study." *Disability and Rehabilitation: Assistive Technology* 17 (2): 134–51. **https://doi.org/10.1080/17483107.2020.1768307**.

Wenig, Dirk, Alexander Steenbergen, Johannes Schöning, Brent Hecht, and Rainer Malaka. 2016. "ScrollingHome: Bringing Image-Based Indoor Navigation to Smartwatches." In *Proceedings of the 18th International Conference on Human-Computer Interaction with Mobile Devices and Services*, 400–406. ACM. **https://doi.org/10.1145/2935334.2935373**.

Yang, Fan, Jian Xiong, Jingbin Liu, Changqing Wang, Zheng Li, Pengfei Tong, and Ruizhi Chen. 2019. "A Pairwise SSD Fingerprinting Method of Smartphone Indoor Localization for Enhanced Usability" *Remote Sensing* 11 (5): 566. **https://doi.org/10.3390/rs11050566**.

Zahabi, Maryam, and David Kaber. 2018. "Identification of Task Demands and Usability Issues in Police Use of Mobile Computing Terminals." *Applied Ergonomics* 66: 161–71. **https://doi.org/10.1016/j.apergo.2017.08.013**.